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FINAL REPORT

APOLLO 17 LUNAR SURFACE COSMIC RAY DETECTOR

NASA Contract #NAS 9-11895

Submitted by:

Robert M. Walker
Principal Investigator
Laboratory for Space Physics
Washington University
St. Louis, Missouri 63130

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I. INTRODUCTION

The Apollo 17 cosmic ray experiment (LSCRE) consisted of a small box containing various detectors of energetic nuclear particles. The box consisted of two parts. When the box was opened one set of detectors was to be hung on the LEM vehicle facing the sun, while the other was to be hung in the shade.

As described in more detail in the accompanying papers, the deployment and recovery of the LSCRE was nominal except for the timing of the termination of the experiment. The experiment was terminated early because of some indications that a small solar storm might be brewing.

Four sets of detectors were included. Mica sheets designed primarily to study solar wind heavy particles were studied by the Washington University group headed by Prof. R. M. Walker in collaboration with Dr. Maurette's group at the University of Paris. Plastic (Lexan) detectors meant to study more energetic particles were analyzed by the University of California, Berkeley group headed by Prof. P. B. Price. Glass detectors, also meant to study more energetic particles, were analyzed by the General Electric group headed by Dr. Robert L. Fleischer. Metal foils designed to measure the flux of light solar wind ions were given to Profs. Geiss and Eberhardt of the University of Berne, Switzerland. Unfortunately, these have not yet been analyzed by our Swiss colleagues.

The experiment had four major objectives. If the sun cooperated by remaining quiet, we intended first to measure the abundance of heavy ions in the solar wind (Washington University). Secondly, we intended to measure the emission of more energetic particles during quiet sun conditions down to lower energies than had heretofore been possible (Washington University, University of California, General Electric). Thirdly, we intended to measure the chemical abundance of low energy particles ($\sim$1 to 10 MeV/nuc) to settle the important question of the galactic or solar origin of these particles. Finally, the metal foils were intended to provide another measurement of the light solar wind gases to complement the more extensive measurements made by the Geiss group on earlier missions.

All of the scientific objectives have been met with the exception of the measurement of the light solar wind gases.

As it turned out, the sun was quite, but not perfectly, cooperative. The initial data available at mission control during the mission indicated that quiet sun conditions prevailed during the full time of exposure. For this reason the initial preliminary reports were couched in terms of "quiet sun conditions". More detailed data that we obtained later showed that this was not strictly true and that very modest solar activity did occur during part of the exposure. Specifically, proton and He fluxes in the range of 29 keV/nuc to 1.8 MeV/nuc as measured on IMP-6, Vela 6A, and IMP-7 rose to levels more than a factor of 10 higher than typical quiet time counts during the second half of the period of deployment. Since only minor subflares were observed in the days before Dec. 13, it is not clear which solar event is associated with this enhancement. Data from Pioneer 10, then at 3.3 AU, for protons and alphas in the energy range from 0.5 to 1.8 MeV/nuc show an enhancement by a factor of 3 to 5 on both days and indicate that this time was a non-quiet period.

II. HEAVY SOLAR WIND EXPERIMENT - ANALYSIS OF MICA DETECTORS

Results from the heavy solar wind experiment have been published in the following letters and papers:

1) R. M. Walker, E. Zinner and M. Maurette, "Measurements of Heavy Solar Wind and Higher Energy Solar Particles During the Apollo 17 Mission," Apollo 17 Preliminary Science Report.

2) M. Maurette, R. Walker and E. Zinner, "Measurements of Extremely Low-Energy VH Ions in Space During a Flare and During 'Quiet' Time Sun Conditions," Proc. 13th Inter. Cosmic Ray Conf. 2 (Univ. of Denver).

3) J. Borg, M. Maurette, R. M. Walker and E. Zinner, "Apollo 17 Lunar Surface Cosmic Ray Experiment - Measurement of Heavy Solar Wind Particles," Lunar Science V (Lunar Science Inst., Houston).

4) E. Zinner, R. M. Walker, J. Borg and M. Maurette, "Apollo 17 Lunar Surface Cosmic Ray Experiment - Measurement of Heavy Solar Wind Particles," Proc. Fifth Lunar Sci. Conf. (to be published).

5) E. Zinner, R. M. Walker, J. Borg and M. Maurette, "Measurement of Heavy Solar Wind Particles During the Apollo 17 Mission," Proc. Third Solar Wind Conf. (to be published).

We anticipate publishing a final paper including more of the experimental details and tying the final numbers to the light ion data to be obtained from the Geiss group. Some exploratory experiments designed to further improve the data are also currently in progress in Maurette's group in Paris. If these bear fruit, then we will return to the further analysis of the mica sheets.

The preliminary results showed a surprising lack of large shallow pits from the expected flux of extremely heavy ions. Subsequent calibration measurements showed that this was caused by a suppression of the density of large pits by the very large background of smaller pits from Fe group ions. This effect had been checked qualitatively, but not quantitatively, prior to flight. The existence of this effect meant a complete new series of calibrations and it is this that delayed finishing the analysis on the projected time scale.

The final results show that iron group ions are perhaps slightly enriched relative to hydrogen compared to what would be expected from the Cameron solar system abundances. Specifically, we find an Fe/p ratio of 4.1×10^{-5} compared to the Cameron estimate of 2.6×10^{-5}.

Unlike solar flare particles, the enrichments do not appear to increase dramatically with increasing mass. The abundances for atomic numbers ≥ 45 are no greater than, at most, a factor of four times the Cameron values.

III. ENERGETIC PARTICLES IN SPACE - ANALYSIS OF THE LEXAN STACK

The analysis of the Lexan stack by the University of California group was highly successful, its main limitation being the small collecting power resulting from weight and size constraints. The following description of the experiment has been provided by Prof. Price:

The procedures for data analysis and the scientific results are described in detail in the following papers, copies of which are attached:

1. P. B. Price and J. H. Chan, "The Nature of Interplanetary Heavy Ions with $0.1<E<40$ MeV/nucleon," Apollo 17 Preliminary Science Report.

2. J. H. Chan, P. B. Price and E. K. Shirk, "Charge Composition and Energy Spectrum of Suprathermal Solar Particles," Proc. 13th Inter. Cosmic Ray Conf. 2 (Univ. of Denver).

3. J. H. Chan and P. B. Price, "Anomalies in the Composition of Interplanetary Heavy Ions with $0.01<E<40$ MeV/amu," submitted to Astrophys. J. Letters.

Several unexpected scientific results of considerable importance emerged. They are discussed in detail in paper 3 and can be distilled into the following statements:

1. During a time when the sun was only slightly active (an enhancement of the 0.5 to 1 MeV/amu alpha-particle flux by $\sim$5 times the quiet-time level occurred halfway through our 45 hour exposure) we found that (a) the energy spectra of interplanetary heavy ions decreased steeply with energy, (b) the absolute levels were higher by 5 to 10x than quiet-time levels, and (c) the abundance ratios were CNO: He = 0.03 and $[Z\geqslant 20]$: CNO = 0.09 at $E<1$ MeV/amu, both of which are enhanced over the solar photospheric ratios. Thus, the

heavy ion enrichments recently observed in strong and in weak flares also occur when the sun is nearly quiet.

2. At energies of 1 to 10 MeV/amu where the contribution of solar particles was small, the composition is anomalous. We confirmed the recent report of McDonald et al. and Hovestadt et al. that there is a plateau in the oxygen spectrum at $\sim$1 to 10 MeV/amu. The shape and magnitude of our oxygen spectrum agree with theirs. In addition, we showed that the spectra of Mg + Si and of $[Z \geq 20]$ steeply decreased in the same 1 to 10 MeV/amu interval, and the LiBeB/CNO ratio is <0.06, indicating that the anomalous oxygen ions cannot have passed through nearly as much matter as have galactic cosmic rays. These results by themselves justify the inclusion of this experiment on Apollo 17.

3. At energies above $\sim$20 MeV/amu the composition, as determined sketchily on Apollo 17 and in more detail with our plastics stack on Apollo 16, is similar to that of galactic cosmic rays at energies >250 MeV/amu.

IV. ENERGETIC PARTICLES IN SPACE - ANALYSIS OF THE GLASS DETECTORS

The results of the analysis of the glass detectors by the General Electric group headed by Dr. R. L. Fleischer have been published in the following three articles, copies of which are attached:

1) R. T. Woods, H. R. Hart, Jr. and R. L. Fleischer, "Quiet Time Energy Spectra of Heavy Nuclei from 20 to 400 keV/amu," Apollo 17 Preliminary Science Report.

2) R. T. Woods, H. R. Hart, Jr. and R. L. Fleischer, "Low Energy, Heavy Cosmic Ray Nuclei During a Solar Quiet Time," paper #299, Proc. 13th Inter. Cosmic Ray Conf. 2 (Univ. of Denver).

3) R. T. Woods, H. R. Hart, Jr. and R. L. Fleischer, "Apollo 17 Cosmic Ray Experiment: The Nature of Interplanetary Heavy Nuclei in the Energy Range of 0.05 to 5.0 MeV/amu"(submitted to the Astrophysical J.).

These authors made careful measurements of the energy spectra of energetic particles impinging on both the sun and shade portions of the LSCRE. The energy spectrum could be characterized very well by a power law in kinetic energy of the form $\frac{dN}{dE} = AE^{-2.7}$. Comparison with satellite data showed an enhanced Fe/α ratio of a factor of 10. The sun detectors gave a factor of two higher flux with similar energy spectra. These facts taken together indicate that most of the particles studied by the G. E. group were solar in origin. They further show that the enrichment of heavy elements at low energies is characteristic of quiet or slightly disturbed solar conditions and not just of larger solar flares.

V. SUMMARY

All of the major objectives of the LSCRE have been accomplished with the exception of the measurement of light solar wind ions by the University of Berne. Important new information on the solar wind and on more energetic particles in the interplanetary medium were obtained. We consider this to have been a highly successful experiment and are grateful to the NASA personnel who made it possible.

19. Cosmic Ray Experiment

INTRODUCTION

The scientific objectives of the lunar surface cosmic ray experiment (LSCRE) were (1) to measure the flux of solar wind particles with atomic number $Z > 26$ using mica detectors, (2) simultaneously to determine the flux of light, rare-gas solar wind ions using metal foils, (3) to measure the flux of low-energy particles in space, both solar and galactic, during quiet Sun conditions using plastic, glass, and mica detectors, and (4) to determine the radon concentration in the lunar atmosphere using mica detectors.

Several different groups, each of which provided different detector materials, collaborated in the experiment. The overall design, construction, and coordination of the experiment were provided by R. M. Walker and E. Zinner of Washington University. The mica detectors are currently being studied by R. M. Walker, E. Zinner, and M. Maurette of the University of Paris. The glass detectors are being studied by the General Electric Company (GE) group of R. L. Fleischer, H. R. Hart, and R. T. Woods. The Lexan plastic is being examined by the University of California group, headed by P. B. Price. The aluminum and platinum foils are being used by P. Eberhardt and J. Geiss of the University of Bern to measure the flux of light solar wind ions in a greatly scaled down version of their solar wind composition experiments.

A much larger particle-detector experiment, with similar objectives and mostly the same investigators, was flown on the Apollo 16 mission. A solar flare that occurred during the Apollo 16 mission made it possible to obtain unique and important information concerning solar flares, particularly at low energies (refs. 19-1 to 19-5). However, the great abundance of solar flare particles created a background that made it impossible to realize many of the original objectives of the experiment.

In mid-1972, a group of investigators proposed the LSCRE particle detector described in this report for the Apollo 17 mission. Because of the short time available before the mission, the proposed experiment was designed to have minimal weight and to require minimal astronaut time on the lunar surface. In part A of this section, a general description of the experiment and its deployment on the lunar surface is given. A status report on the scientific results being obtained with the mica detectors is also presented. In parts B and C, the results obtained with the glass and Lexan detectors, respectively, are described. At the time of preparation of this report, no data were available on the solar-wind-implanted metal foils.

PART A

MEASUREMENTS OF HEAVY SOLAR WIND AND HIGHER ENERGY SOLAR PARTICLES DURING THE APOLLO 17 MISSION

R. M. Walker,[a] *E. Zinner,*[a] *and M. Maurette*[b]

DESCRIPTION OF THE EXPERIMENT

In the Apollo 17 lunar surface cosmic ray experiment (LSCRE), one set of particle detectors was mounted inside a shallow, rectangular aluminum box; a separate set was mounted inside a sliding cover (fig. 19-1). The box was deployed in sunlight and the sliding cover in shade. The detectors mounted in each part are listed in table 19-I; the detector numbers are keyed to figure 19-1(c). Both the Sun half and the shade half had temperature labels on the sides opposite those on which the detectors were mounted.

In each half, the mica detectors (numbers 1 and 13 in fig. 19-1(c)) consisted of a single slab of cleaved muscovite that had been previously annealed for 100 hr at 853 K in an argon atmosphere to remove fossil tracks. The mica detector also had 18 spots, each 0.24 cm in diameter, of evaporated silver deposited on the external surface to aid in distinguishing solar wind particles from more energetic, penetrating particles. One-third of these spots had a metal thickness of ≈55 nm; the remaining two-thirds were equally divided between thicknesses of ≈100 and ≈150 nm. The mica plates were held in position with two metal straps and were also lightly tacked down with spots of Dow Corning 6-1104 silicone glue.

Two mica detectors (number 6 in fig. 19-1(c)) were also mounted in rectangular recesses milled in the edge of the Sun half. The purpose of these auxiliary mica detectors was to determine the precise orientation of the Sun during exposure from the shadowing of solar wind tracks by the edges of the recess. Because the mica was intended primarily to detect solar wind particles, careful microphotographs of all mica pieces were taken using oblique lighting, both before and after the mission, to assess the degree of dust covering.

The 5-μm-thick platinum and aluminum foils (numbers 2, 3, and 12 in fig. 19-1(c)) were glued to 1.5-mm-thick aluminum with 3M 467 adhesive film. The plates were in turn glued into the box and cover. In addition, two platinum foils 5 by 0.8 and 9.5 by 0.8 cm were glued into recesses on the sides of the box (numbers 7 and 8 in fig. 19-1(c)). The different orientations of foils as well as the use of different metals (platinum and aluminum) were to provide redundant information on the direction of the light solar wind and also to look for a flux of low-energy ions at large angles to the solar wind direction.

The glass detectors (numbers 4, 5, 9, and 10 in fig. 19-1(c)) are described in more detail in part B of this section. For a description of the Lexan detector (number 11 in fig. 19-1(c)), see part C.

The LSCRE was transported to the Moon in the closed position, in which both sets of detectors were inside the box. In this position, the end rings, one attached to the box and one attached to the cover, were on opposite sides of the box. The cover was held in place by spring loading and also by a Velcro strap, attached at one end to the end ring on the box, looped around the entire assembly. To avoid contamination, the LSCRE was transported to the Moon in a plastic bag inside the lunar module (LM) cabin. The total weight of the assembled package was 163 g, and the overall dimensions were 22.5 by 6.3 by 1.1 cm.

DEPLOYMENT AND RECOVERY ON THE LUNAR SURFACE

The LSCRE was deployed by first pulling the slide cover off while in the shade of the LM and hanging the cover in place on a hook attached to the side of the LM. The cover remained in the shade, with the detectors pointed toward space, for 45.5 hr. After deployment of the cover, the box portion of the LSCRE was carried into sunlight and hung on the strut of the LM using the Velcro strap attached to the end ring. Deployment was nominal and was completed early in the first period of extravehicular

[a]Washington University, St. Louis, Missouri.
[b]Laboratoire René Bernas, Orsay, France.

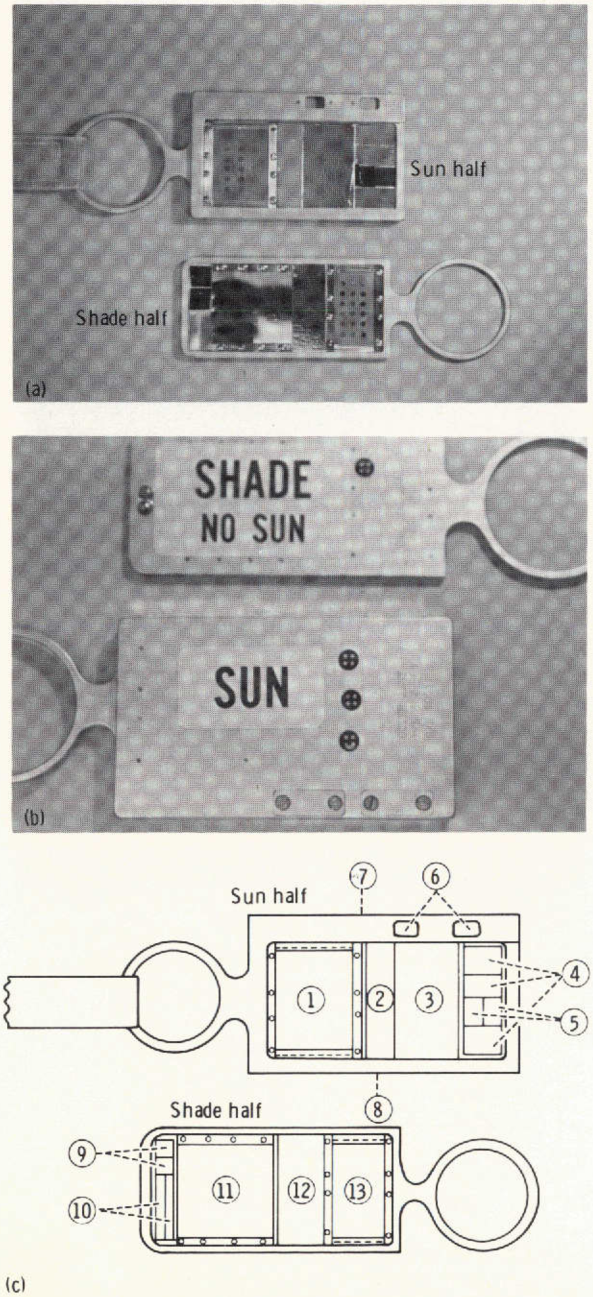

FIGURE 19-1.–The LSCRE. (a) View of interior. (b) View of exterior. (c) Schematic diagram. For information on numbered detectors, see table 19-I.

activty (EVA) at 01:23 G.m.t., December 12, 1972 (118:30 GET).

The location of the two sets of detectors is shown schematically in figure 19-2. The Sun-half detector set is shown deployed on the lunar surface in figure 19-3. The exact orientation of the Sun half with respect to the Sun has not yet been precisely determined. However, the lack of shadowing in the photograph (fig. 19-3), taken at the time the experiment was terminated, shows that the Sun-half detector must have been close to being perpendicular to the Sun line as stated by the LMP at the time of initial deployment. The Sun elevation angle changed from 13° to 34° during the time the experiment was deployed; the corresponding total change in azimuth angle was 10°.

Because of the possibility of a substantial enhancement in the flux of interplanetary particles, the experiment was terminated at the beginning of EVA-3 instead of at the end, as originally planned. The experiment was terminated by the LMP, who first removed the Sun-half detector and then walked into the shade and mated it with the shade-half detector. The latter was thus never exposed to the Sun. The LSCRE was then placed in a plastic bag for transport back to Earth. The total exposure time was 45.5 hr.

TABLE 19-I.–*Detectors in the LSCRE*

Number	*Detector*	*Component measured*	*Exposed area, cm^2*
		Sun-half detectors	
1	Mica	Heavy solar wind and low-energy cosmic rays	12.2
2	Aluminum foil	Light solar wind	5.1
3	Platinum foil	Light solar wind	11.2
4	Fused quartz (Suprasil 2)	Low-energy cosmic rays	5.4
5	Lead phosphate glass (Lal)	Low-energy cosmic rays	1.85
6	Mica	Heavy solar wind (Sun direction)	1.2
7	Platinum foil	Light solar wind	3.8
8	Platinum foil	Light solar wind	8.0
		Shade-half detectors	
9	Lead phosphate glass (Lal)	Low-energy cosmic rays	1.76
10	Phosphate glass (GE-1457)	Low-energy cosmic rays	1.62
11	Lexan	Low-energy cosmic rays	14.0
12	Platinum foil	Control piece for foils in Sun	6.8
13	Mica	Low-energy cosmic rays and radon atmosphere	9.1

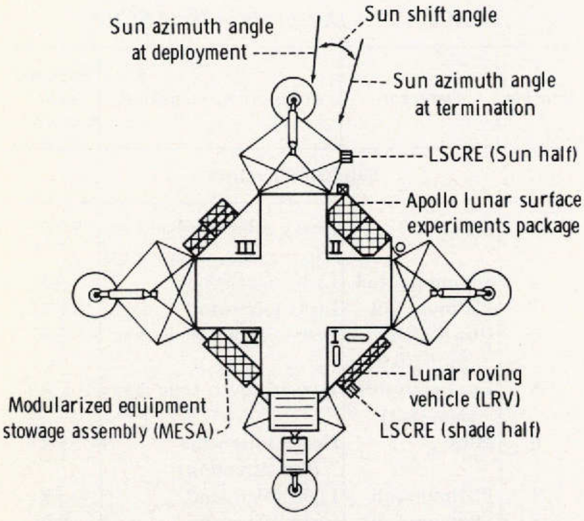

FIGURE 19-2.–Schematic top view of the LM showing the locations of the Sun half and the shade half of the deployed LSCRE as well as the azimuthal Sun angle at the time of deployment and at the time of termination of the experiment.

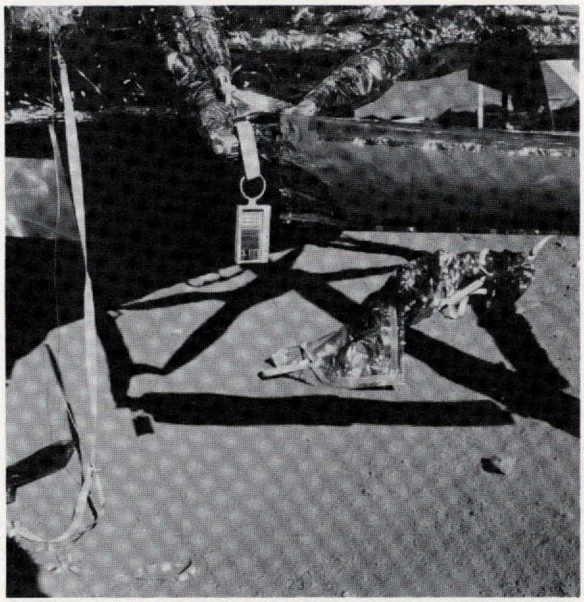

FIGURE 19-3.–The Sun half as deployed on the Moon. This photograph is one of a pair of stereoscopic pictures taken by the lunar module pilot (LMP) from a distance of 2.13 m (7 ft) immediately before termination of the experiment (AS17-140-21381 and 21382). Another pair of stereoscopic photographs was taken of the shaded portion (AS17-140-21383 and 21384).

Examination of the detector package after its reception in the investigators' laboratory showed that the detector surfaces were in an essentially pristine condition. Less than 5 percent dust cover was observed on the mica and the metallic foils, and it is clear that the detectors had not been touched by the astronaut in the deployment and termination sequences. The temperature labels indicated that temperatures of the Sun-half detectors had reached 393 K but stayed below 403 K; the shade-half detectors were always cooler than 316 K. The temperature of the Sun-half detector was somewhat higher than anticipated but well below the design limit of 423 K.

SOLAR ACTIVITY IMMEDIATELY BEFORE AND DURING THE APOLLO 17 MISSION

During the period December 11 to 13, 1972, there were two major active regions on the Sun. Region 496, which reached an apparent optical maximum on December 12, produced only a few subflares. Region 500, which emerged on December 10 and 11, also produced only minor subflares during the period December 11 to 13. At 14:55 G.m.t. on December 13, an eruptive prominence was observed on the eastern limb. Figure 19-4 is an optical photograph showing the active solar regions.

The following satellite proton monitor channels showed no significant increase above background during the entire Apollo 17 mission.

Satellite	*Channel energy range, MeV*
[a]IMP-G	> 10, > 30, > 60
IMP-H	> 8, > 25, > 95
IMP-I	> 10, > 30, > 60
Pioneer 9	> 13.9, > 40
Vela	0.88 to 3.2, 3.2 to 5, 7.7 to 12

[a]IMP = Interplanetary Monitoring Platform.

In contrast, monitors on board the first Applied Technology Satellite (ATS-1) and the lower energy channels on Vela showed significant increases throughout most of December 13, 1972. In particular, the ATS-1 3- to 21-MeV channel showed a slow increase starting at 08:52 G.m.t. on December 13 and a more pronounced increase at 15:00 G.m.t. on December 13. During the quiescent period before 08:52 G.m.t. on December 13, the counting rate was 0.38 proton/ cm^2/sec. During the period from 08:52 to 15:00 G.m.t. on December 13, the average rate

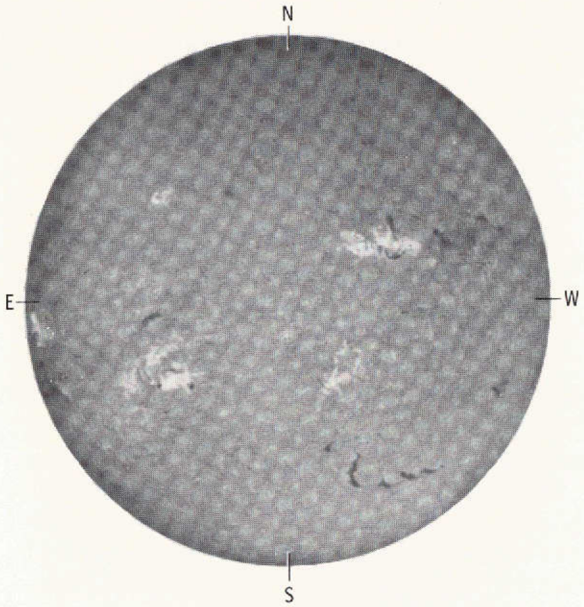

FIGURE 19-4.–The Sun as observed in hydrogen alpha: The photograph was taken at 09:35 G.m.t., December 13, 1972, through the optical telescope on Canary Island, one of the Solar Particle Alert Network sites.

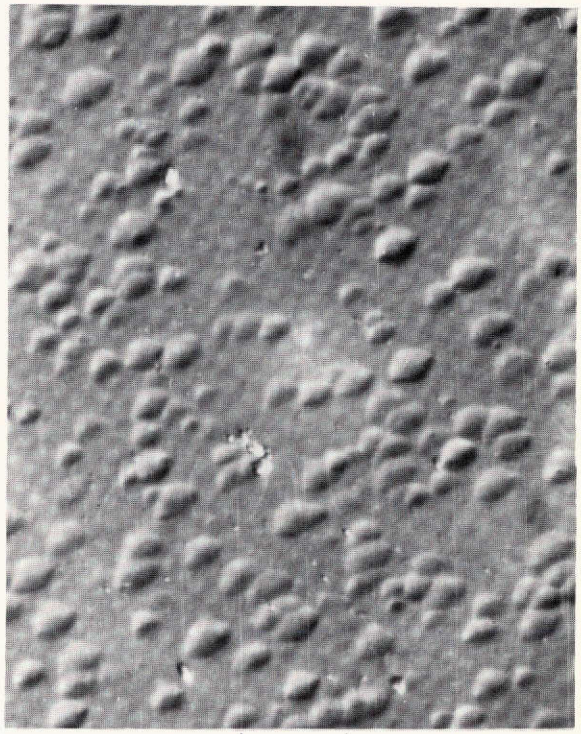

FIGURE 19-5.–Surface of mica showing pits of 1-keV/nucleon xenon ions. After the surface was bombarded with the ions, the mica was etched for 2 hr in 40 percent HF at 303 K. The photograph was taken on Kodak high-contrast copy film through a Leitz microscope using the Smith interference contrast method in reflected light.

increased to 2.0 protons/cm^2/sec. From 15:00 G.m.t. on December 13 to the time the experiment was terminated (22:53 G.m.t.), the average counting rate was 5.3 protons/cm^2/sec. No significant increase above background was observed in the 21- to 70-MeV channel.

Possibly more significant for this experiment are the results from the low-energy proton channels on the Vela satellite. Starting at approximately 04:00 G.m.t. on December 13, the 0.20- to 0.47-MeV channel showed an increase to a new level of $\approx$45 protons/cm^2-sec-sr-MeV from the previous background of $\approx$7 protons/cm^2-sec-sr-MeV. A similar increase from 1.3 to $\approx$6.5 protons/cm^2-sec-sr-MeV was observed in the 0.47- to 0.88-MeV channel. These higher levels were maintained for the rest of the time the experiment was exposed on the Moon and contributed to the decision to terminate it earlier than planned.

In the period immediately before the mission, one energetic solar event occurred early on November 28; thereafter, solar activity was very low. The November 28 event was a class M1 event from active region 483. No proton enhancement was observed near the Earth, but the Pioneer 6 and 7 spacecraft observed enhanced 0.6- to 13-MeV proton fluxes on November 29.

In summary, the period immediately before and during the mission was one of relatively low, but not completely negligible, solar activity.

OBSERVATION OF HEAVY SOLAR WIND PARTICLES

When mica is irradiated with heavy ions having energies of $\approx$1 keV/nucleon, subsequent etching produces shallow etch pits (fig. 19-5). Although the physical reasons are not well understood, it is found empirically that the diameters of the etch pits depend on the charge of the bombarding particles. For example, after 2 hr of etching at 303 K in a 40-percent solution of hydrofluoric acid (HF)–the standard etch treatment for all results reported herein–we find that manganese ions produce very small pits (<1 μm), whereas heavier ions produce larger pits as follows: krypton, ≈2.1 μm; xenon, ≈3.0 μm; and lead, ≈4.9 μm.

This dependence of etch-pit size on the charge of the bombarding particles is the basis for the attempt to determine directly the abundance of extremely heavy ions in the solar wind. Although the average pit size is a monotonically increasing function of charge, any given ion results in a range of pit sizes that is quite large. For this reason, the experiment does not permit a precise determination of the charge of individual ions; rather, it gives a statistical sampling of broad groups of ions.

We have found empirically that the average pit size is not strongly dependent on the orientation of the beam with respect to the mica. At shallow incident angles to the surface, however, the distribution of pit sizes becomes somewhat narrower. The range of the angles of incidence of the solar wind is such that no effect on the registration properties of heavy ions is expected.

Because the registration of very-low-energy ions is not well understood either theoretically or experimentally, the possibility exists that subtle differences in the physical state of different mica samples may affect the track registration properties. For this reason, a complete set of recalibration experiments has been undertaken on the micas that were actually sent to the Moon. These calibrations are not yet complete; for this reason, the results reported here are mostly qualitative.

The results are also preliminary because only the crudest and quickest method of observation has been used. In practice, three methods can be used: interference contrast optical microscopy, transmission electron microscopy, and scanning electron microscopy. After a 2-hr etch, producing wide pits (as much as 6 μm in diameter), the pits are easily observed by interference contrast optical microscopy. In this technique, the surface is first silvered and then observed either in a Zeiss microscope using the Nomarski interference system or in a Leitz microscope using the Smith interference system. In our experience, the two systems seem to be roughly equivalent, with the former giving somewhat higher resolution and the latter somewhat better contrast. These differences, however, may have resulted from imperfect alinement of either or both of the systems.

The optical microscope is capable of giving relatively quick results, but the large pit sizes involved have two consequences. When the density of tracks is large (as is the case here), the pits overlap and the occasional large pits tend to be obscured. In principle, observation of surface replicas of briefly etched samples using a transmission electron microscope should give more detailed measurements than those reported herein. Scanning electron microscopy of lightly etched surfaces is possible in principle, but we have not been able to get enough contrast in the images to make this technique practicable.

In figures 19-6 to 19-9, it is shown that heavy solar wind ions are registering in the mica as expected. Figure 19-6 shows a sample of mica exposed on the Sun half that has been etched for 2 hr in a 40-percent HF bath at 303 K. The photograph was obtained using the Smith interference system. The surface is clearly covered with a background of small, shallow pits, present in such abundance as to be unresolvable. The estimated concentration of solar wind ion atoms was 1.2×10^9 atoms/cm^2; laboratory irradiations with 1×10^9 atoms/cm^2 manganese ions of 1 keV/nucleon produce a similar background at the same etch time. A region of the Sun-exposed mica

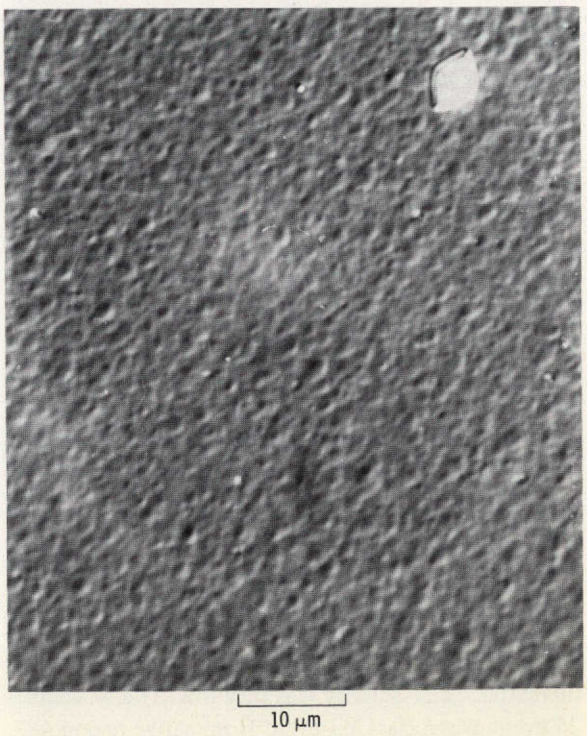

FIGURE 19-6.–Mica surface of LSCRE exposed to sunlight during 45.5 hr on the Moon. Etching and microphotography conditions were the same as those for figure 19-5.

that was covered with a 0.5-mm-thick stainless steel strap is shown in figure 19-7. Clearly, the bulk of the particles causing the shallow background have been stopped by the strap. In figure 19-8, a region of the Sun-half mica that was covered with ≈150 nm of silver is shown. Again, a striking difference is observed in the background of very shallow pits. Finally, in figure 19-9, an etched sample of the shaded mica is shown. The extensive background of shallow pits is again missing.

Although the extensive shallow pit background is missing in those areas of mica not exposed directly to the Sun, all areas of both the shade-half and Sun-half micas contain a considerable density of deep pits corresponding to higher energy particles. Figure 19-10 is a scanning electron microscope photograph of one such deep pit. Because of the relatively quiescent behavior of the Sun during the Apollo 17 mission, these higher energy particles were not expected. They are discussed separately in the section entitled "Energetic Solar Particles."

The photographs (figs. 19-5 to 19-9) illustrate another effect that complicates the analysis of the solar wind composition. In addition to the bright (deep) pits, the covered and shaded portions of the mica contain a low background of shallow, broad pits. These pits were probably produced by high-energy ions similar to those producing the bright pits, but of lower mass. Particles such as 100-keV/nucleon oxygen are capable of producing pits (ref. 19-6) caused by occasional, damage-producing, close nuclear encounters with the near-surface atoms of the mica detectors. These pits thus constitute a background that must be subtracted to obtain information about extremely heavy solar wind ions.

Close examination of figures 19-7 to 19-9 further shows that the mica that was covered with 150 nm of silver has a higher background of very small, shallow pits than either the mica that was exposed in the shade or the Sun-half mica that was covered with the metal strap. Contrary to expectations, some solar

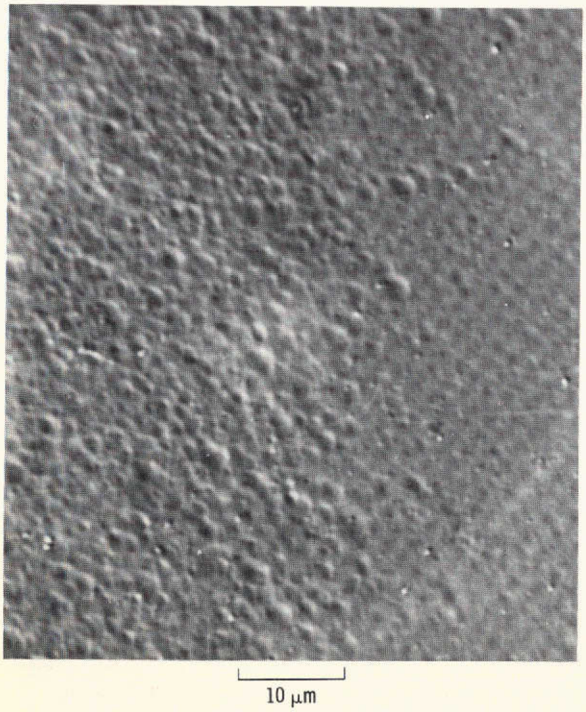

FIGURE 19-7.–Mica surface from the sunlit portion of the LSCRE. The right half of the picture shows an area under a 0.5-mm-thick steel strap. Etching and microphotography conditions were the same as those for figure 19-5.

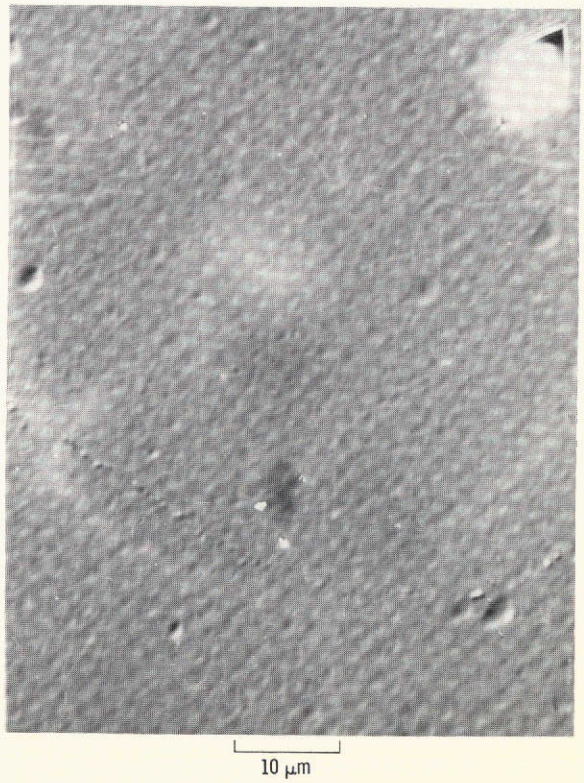

FIGURE 19-8.–Mica surface from the sunlit portion that was covered with 150 nm of silver during exposure. Etching and microphotography conditions were the same as those for figure 19-5.

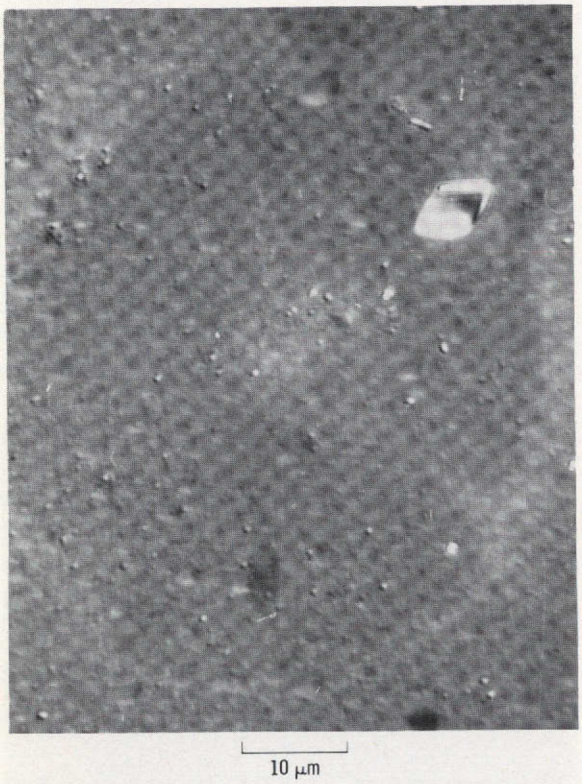

FIGURE 19-9.–Mica surface from the shaded portion of the LSCRE. Etching and microphotography conditions were the same as those for figure 19-5.

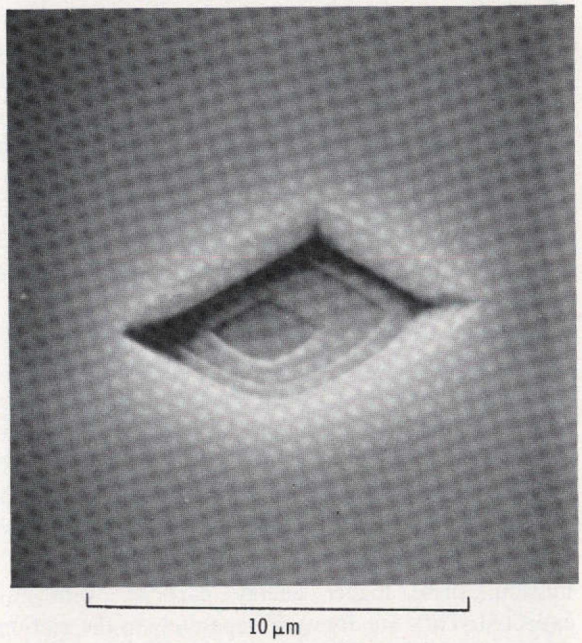

FIGURE 19-10.–One of the deep pits produced by energetic heavy particles as seen on the Sun-half mica. The photograph was taken in a scanning electron microscope. Similar tracks from energetic particles are seen in the mica exposed in shade (fig. 19-9).

wind ions are apparently capable of penetrating the 150 nm of silver. Additional measurements on the mica regions covered with 50 to 100 nm of silver should clarify this point.

For this preliminary analysis, the periodic table above charge $Z = 30$ has been divided into three broad groupings of elements. The first, consisting of charges from 30 to 40 (group I), is much more abundant than the others, which include $Z = 40$ to $Z = 60$ (group II) and the group of charges from 60 to 92 (group III). (Most of group III is made up of elements of $Z = 78$ and $Z = 82$.) The expected pit densities in various size ranges from these three groups are summarized in table 19-II. The contribution of the group I elements to the expected density of pits may be overestimated by as much as a factor of 3 because an efficiency of pit registration of unity in this range has been assumed; in reality, the efficiency may be as low as 0.3. The registration efficiency of the group II elements is at least 50 percent; of the group III elements, it is essentially 100 percent.

Also shown in table 19-II are the experimental results obtained to date for pits >2 μm in diameter. The results are not in good agreement with the calculated values. In particular, the experimental values for large pits are much lower than expected. To fit the predicted values, eight pits >4 μm in diameter and four pits >5 μm in diameter should have been seen in the area scanned; none, in fact, were observed.

Taken at face value, this deficiency would imply a depletion of both group II and group III elements in the solar wind. In view of existing measurements of xenon abundances in both lunar samples and meteorites, a depletion of group II elements seems most unlikely. A more likely explanation is that the larger shallow pits have been obscured by the large background of small, iron-group pits developed by the long etching times used in this first-scan look. More detailed measurements using shorter etching times are in progress. If the apparent depletion is still found in these experiments, then the effects of other factors,

TABLE 19-II.–*Pit Density Distribution*

Pit size, μm	*Track density, tracks/cm²*				
	Calculated contribution[a] of group–			*Total*	*Measured*
	[b]*I*	[c]*II*	[d]*III*		
1 to 2	2.1×10^5	9×10^3	0	2.2×10^5	–
2 to 3	2.25×10^5	0.15×10^5	0	2.4×10^5	7.5×10^5
3 to 4	5.6×10^4	1.2×10^4	0.2×10^4	7×10^4	3.0×10^4
4 to 5	5.8×10^3	5.9×10^3	5.0×10^3	1.7×10^4	–
5 to 6	0	1.6×10^3	5.1×10^3	6.7×10^3	–
6 to 7	0	0	1.0×10^3	1.0×10^3	–

[a]Based on solar abundances.
[b]Atomic numbers 30 to 40.
[c]Atomic numbers 40 to 60.
[d]Atomic numbers 60 to 92.

principally the potential fading of tracks by solar ultraviolet irradiation, will have to be pursued before any final conclusions can be reached.

ENERGETIC SOLAR PARTICLES

As previously noted, both the shade-half and Sun-half mica detectors had numerous bright pits corresponding to longer tracks. Scanning by normal transmission optical microscopy, where the shallow pits are not observable, gave consistent track densities of $6.4 \pm 0.6 \times 10^3$ tracks/cm² for a shade-half sample and $5.8 \pm 0.6 \times 10^3$ tracks/cm² for a Sun-half sample. The high-energy particles therefore are distributed isotropically in space and appear to have no relationship to the solar wind. From comparison with scanning electron microscope data, it is estimated that the track densities obtained by optical microscopy correspond to pits $\gtrsim 0.5$ μm in depth.

Although much higher in energy than the solar wind, the particles being detected have rather modest energies in comparison with many solar flare particles or galactic cosmic rays. Only four tracks corresponding to iron ions of $\gtrsim 1$ MeV/nucleon were found in a scan of a 0.5-cm² area.

The distribution of track densities compared to energy, assuming registration of iron ions only, is shown in figure 19-11. Two curves are shown: in one, the measured track length has been taken as a measure of the total range of the iron ions; in the other, it is assumed that iron ions do not register in the last 1.7 μm of their range. This estimate of the "range deficit" is taken from the work of Blok et al. (ref. 19-7), in which the etching time used was only 20 min instead of 2 hr as used in this study and the etching temperature was only 293 K as opposed to 303 K. Whereas our previous work has shown that, in other mica samples etched with our conditions, 30-keV/nucleon nickel ions produce pits with depths of 0.75 μm as compared to calculated ranges of 1.0 μm, recent preliminary calibration data show that iron ions of the same energy result in only very shallow pits (<0.1 μm deep) in the mica used in this experiment. These results indicate that the registration of low-energy ions in mica varies with the particular sample and might depend strongly on its annealing history. The long etching times (chosen for examination of shallow pits) made it difficult to measure lengths below ≈5 μm with precision, and the lower energy points are probably somewhat underestimated. Additional measurements are in progress using a transmission electron microscope on replicas from the mica. Until these measurements have been made and final calibration data on the range deficit are obtained, the curves in figure 19-11 should be considered as lower limits on the fluxes of particles in this energy range.

The assumption that only iron ions are responsible for the tracks is not strictly correct because ions as light as neon can produce tracks toward the end of their range. As previously noted, even low-energy oxygen ions can give observable, shallow pits. As shown in the report on the Apollo 16 cosmic ray experiment (ref. 19-3), inclusion of lighter ions would have the net effect of flattening somewhat the apparent energy spectrum shown in figure 19-11. In view of the uncertainties in the range-deficit problem and the fact that calibration data for the particular mica in question will soon be available, the light ion correction has not been included in figure 19-11.

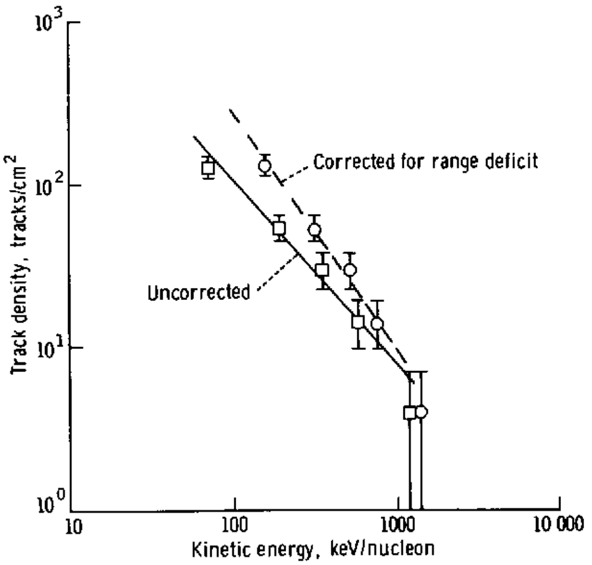

FIGURE 19-11.–Integral energy spectrum of the energetic iron particles observed in the sunlit and shaded micas. One set of points (squares) is obtained by assuming the tracks are etched for their total range. The circled points are plotted assuming a range deficit of 1.7 μm as given by Blok et al. (ref. 19-7).

The integral energy spectrum shown in figure 19-11 can be fitted between 80 keV/nucleon and 1 MeV/nucleon by a power law of the form $N(>E) = KE^{-\gamma}$ with spectral index $\gamma = 1.1$, where N is the track density, E is the kinetic energy, and K is a constant. Adding the maximum range deficit to the data only changes the exponent γ slightly to 1.3. The Apollo 16 flare data showed a similar power law dependence, but with a larger value of γ of ≈ 2. Long-term values of solar flare very-heavy particle ($20 \leqslant Z \leqslant 28$) energy spectra derived from studies of lunar rocks are intermediate between the values measured here and in the Apollo 16 experiment. Although it cannot be proved that the high-energy particles observed in this experiment are solar in origin, the general similarity of the energy spectrum to that observed in solar flares strongly suggests that they originate in the Sun.

Although probably solar in nature, the precise source of the particles is unclear. As outlined in the section entitled "Solar Activity Immediately Before and During the Apollo 17 Mission," although the Sun was generally quiescent, some activity was observed. Particle counting rates also rose considerably above background at low energies early on the morning of December 13, 1972. Possibly, the particles observed were directly associated with this rather modest solar activity. They could also represent particles stored in the interplanetary regions from earlier solar emissions. Here again, however, the solar activity was rather modest immediately before the mission. The possibility that the Sun emits a more or less continuous flux of such low-energy particles, independent of any visible solar activity, cannot be ruled out. Testing this point will require additional measurements of extremely low energy particles outside the magnetosphere.

Lunar sample investigators have normally attributed fossil track observations of low-energy particles to the influence of solar flares. The present result confirms this interpretation. The quiet-time fluxes measured in this experiment, although higher than expected, are simply too low to account for the lunar observations. In this connection, it should be noted that the rather modest flare observed during the Apollo 16 mission contributed 200 times as many track-producing particles as were observed in this experiment.

LIMITS ON THE RADON ATMOSPHERE AT THE APOLLO 17 SITE

Recoiling atoms from alpha-particle decay processes have kinetic energies similar to those in the solar wind. It was, in fact, the observation of fossil alpha-particle recoil tracks in terrestrial micas (ref. 19-8) that originally led to the suggestion that mica could be used as a heavy solar wind monitor. Two important sources of alpha-particle recoil tracks are radon-222 (^{222}Rn) atoms in the lunar atmosphere and corresponding polonium-210 (^{210}Po) atoms that should be deposited on the surface from prior ^{222}Rn decay.

Assuming that recoils of polonium atoms from the surface register with unity efficiency, the total number of alpha-particle recoil tracks per square centimeter per second should be approximately the same as the number of alpha particles per square centimeter per second from ^{222}Rn decay measured in a detector the surface of which is normal to the lunar surface. In a preliminary scan of the shaded mica, only one pit >5 μm in diameter was found in an area of 2.8×10^{-4} cm^2. Because half of all alpha-particle recoil tracks should have diameters greater than this value, we conclude that the density of alpha-particle recoil tracks is $\lesssim 1 \times 10^4$ tracks/cm^2. This density gives an equivalent upper limit on the alpha-particle recoil production rate of ≈3.6 disintegrations/min/cm^2. This value is considerably higher than the most recent orbital measurement of the lunar average of ≈0.06 disintegration/sec/cm^2 by Gorenstein and Bjorkholm (ref. 19-9), but is comparable to earlier measurements of ≈1.2 disintegrations/min/cm^2 for each alpha-active ^{222}Rn daughter measured on the Surveyor V, VI, and VII spacecraft (ref. 19-10). The present statistics are clearly too poor to comment further on this problem.

SUMMARY

The LSCRE, consisting of sets of mica, glass, plastic, and metal foil detectors, was successfully deployed on the Apollo 17 mission. One set of detectors was exposed directly to sunlight and another set was placed in shade.

Preliminary scanning of the mica detectors shows the expected registration of heavy solar wind ions in the sample exposed directly to the Sun. The initial results indicate a depletion of very-heavy solar wind ions. The effect is probably not real but is caused by scanning inefficiencies.

Despite the lack of any pronounced solar activity, energetic heavy particles with energies extending to >1 MeV/nucleon were observed. Equal track densities of ≈6 × 10^3 tracks/cm^2 of tracks ≳0.5 μm in length were measured in mica samples exposed in both sunlight and shade. The energy spectrum of these particles can be represented as a power law of the form $N(>E) = KE^{-\gamma}$ between 60 keV/nucleon and 1 MeV/nucleon. The value of γ of 1.1 is somewhat lower than the long-term average of ≈1.5 measured in studies of low-energy particles in lunar samples, but the general agreement in the nature of the energy dependence suggests that the particles are solar in origin.

The fluxes of these quiet-time energetic particles are too low to account for very many of the fossil tracks seen in lunar samples. As has commonly been assumed, the fossil tracks appear to have been produced predominantly in solar flares.

A preliminary upper limit of ≈3.6 disintegrations/min/cm^2 was obtained for the flux of recoiling nuclei from alpha-particle decay processes such as ^{222}Rn decay in a local lunar atmosphere.

ACKNOWLEDGMENTS

We thank P. Swan of Washington University for invaluable help in the preparation and examination of many of the mica samples. We also appreciate the permission of I. D. Palmer of Los Alamos Scientific Laboratories and G. Paulikas of Aerospace Corporation to quote their preliminary satellite proton data.

PART B

QUIET TIME ENERGY SPECTRA OF HEAVY NUCLEI FROM 20 TO 400 keV/amu

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

The main objective of the General Electric (GE) portion of the Apollo 17 cosmic ray experiment was to measure the abundance and energy spectra and, hopefully, to infer the origin of heavy low-energy nuclei at solar quiet time. The experiment consisted of three varieties of glass solid-state track detectors, which were exposed on the surface of the Moon for 45.5 hr from December 11 to 13, 1972. The detectors were arrayed in two groups, one of which was exposed facing the Sun and the other in the shade facing away from the Sun.

In December 1972, solar activity was approaching the minimum predicted to occur in 1975, and the activity in December 1972 should have been lower than at any time since 1966. As a result, the diminution by the solar magnetic field irregularities of the flux of galactic cosmic rays entering the solar

[a]General Electric Research and Development Center.
[b]State University of New York at Albany.

system (so-called "solar modulation") should also have been approaching its minimum. Characteristically, the fluxes of these galactic particles have been observed to decrease with decreasing energy in the range from a few hundred MeV/amu to the lowest energies previously measured ($\approx$ 40 MeV/amu for heavy nuclei) (ref. 19-2). In contrast, solar flare particles are found, generally, to decrease in abundance with increasing energy (ref. 19-11) and, specifically, for heavy nuclei in the same energy range as that considered in this part (refs. 19-2 to 19-5). The primary key for deciding whether the low-energy nuclei are solar or galactic in origin appears, therefore, to be the slope of the energy spectrum—a positive slope being the signature of the galactic particles and a negative slope being characteristic of solar nuclei.

As a secondary objective, compositional abundances and energy dependence of specific ions will be sought. These will then be compared with compositional measurements made on the Apollo 16 cosmic ray experiment, during which a solar flare occurred.

DESCRIPTION OF DETECTORS

The detectors consisted of nine different pieces of glass of types and total areas listed in table 19-III. The fused quartz (silicon dioxide (SiO_2)) and phosphate glass (GE-1457) detectors were pre-etched and examined before the experiment to ensure a good surface. Small corner portions of each type of glass were preirradiated (with californium-252 (^{252}Cf) fission fragments for SiO_2 and GE-1457 glass and with oxygen 16 (^{16}O) ions for the lead phosphate glass) to determine whether any thermal alteration of tracks occurred during the flight.

TABLE 19-III.–*Apollo 17 Glass Detectors*

Type	*Designation*	*Exposed area, cm²*	
		Sun	*Shade*
Fused quartz (FQ)	FQ-SiO_2 (Suprasil 2)	5.4	0
Phosphate[a]	GE-1457	0	1.62
Lead phosphate[b]	Lal	1.85	1.76

[a]6.30 weight percent phosphate, 11.03 percent barium oxide, 9.30 percent silver oxide, 8.47 percent potassium oxide, and 8.20 percent aluminum oxide.

[b]77.4 percent lead phosphate, 10 percent manganese phosphate, and 12.6 percent iron phosphate, melted in a mullite crucible (D. Lal, personal communication, 1972).

PROCEDURE AND RESULTS

Particle tracks, such as are illustrated in figure 19-12, were revealed under carefully controlled etching conditions with a fixed temperature bath, a fixed etchant stirring rate, and fresh etchant at each separate stage of etching. The general chemical attack

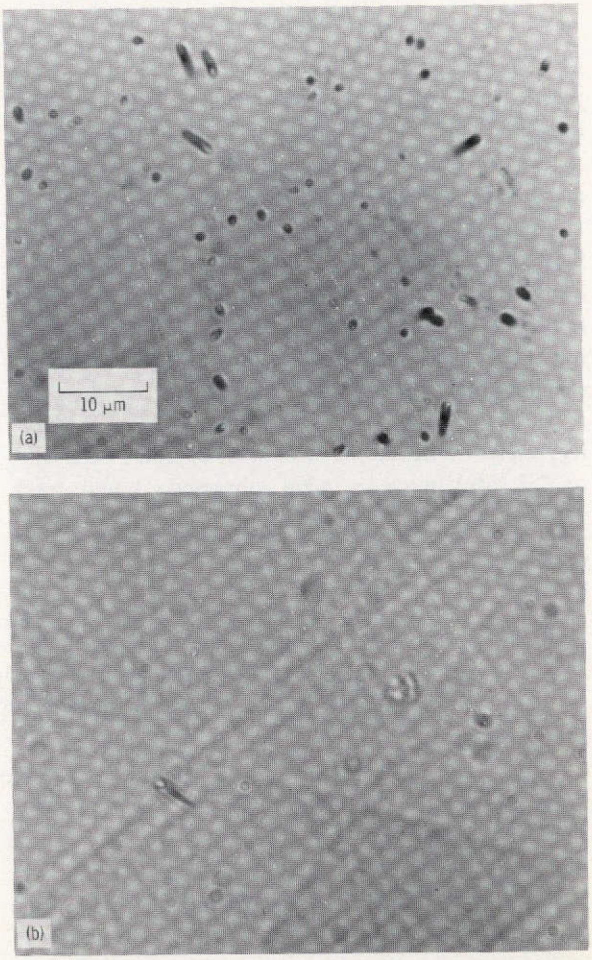

FIGURE 19-12.–Etched tracks in phosphate glass (GE-1457). (a) A typical view in the Apollo 16 detector, which was exposed during a solar flare known to have ejected particles into the interplanetary medium. (b) An atypical view in the Apollo 17 detector. The view is unusual in that it contains a track. Each detector was etched in 48 percent hydrofluoric acid to remove 0.5 × 10^{-4} cm of glass.

rate V_g was measured first, using control samples, by three methods: from the rate of motion of a right-angled edge relative to fixed markers in the glass, from the attack rate inferred from cone angle and track diameter measurements on individual tracks, and from the thickness change of glass plates with parallel faces. When a flight sample was etched, simultaneous and independent measurement of the general attack rate was made and checked with a predicted etch rate for consistency.

The GE-1457 glass was etched in 48 percent hydrofluoric acid (HF) for 5.0 min at 302.45 K to remove 0.5×10^{-4} cm of glass. Track measurements on each track were made more than once using a Leitz Ortholux microscope at a nominal magnification of 1000X and a filar eyepiece, which has a movable hairline. The threshold capability of the eyepiece was checked by an independent experiment. A group of identical glass samples of glass microscope slides was irradiated with ^{252}Cf fission fragments at normal incidence. Samples were then etched under identical etch conditions but in successive increments of 15-sec intervals in 5.7 percent HF at 295.45 K. Track diameter measurements allowed plotting of the track diameter as a function of etch time. For the range of track lengths examined, linearity is expected in track diameters because there is very little change in the cone angle. A straight line was obtained; this result implied that reliable dimension measurements are possible to a lower optical limit of 0.35×10^{-4} cm. Individual tracks were cataloged by constructing a grid-work matrix with each matrix element corresponding in row and column to that of each field of view seen through the optical microscope. This procedure makes possible the relocation of an individual track for remeasurement after successive etches. Individual particle range calculations were then made.

The differential energy spectrum in figure 19-13 was obtained starting with the measured track length distribution given in table 19-IV, in which the results are summarized. Tracks were grouped in length bins, and equivalent energies corresponding to the lower and upper limits were obtained using range-energy tables (ref. 19-12) for iron ions in aluminum, because the GE-1457 glass is closely similar to aluminum in its stopping power. This approximation introduces negligible additional errors. The energy between these two limits was evaluated so that the same number of particles within that bin fall on either side of the energy representing the bin. It was assumed for the purposes of calculation that all particles were from the iron group with a cone angle of $\approx 7°$. This glass is sensitive to ions as light as neon, and it may contain tracks from ions lighter than those in the iron peak. Cone angle measurements are in progress and will be compared with existing calibration data that give cone angles of 30° to 35°, 10°, and 5° to 10° for neon, argon, and iron, respectively (ref. 19-4). It is hoped that the different chemical constituents that are present can be separated in this manner.

The resulting energy spectrum extends from a kinetic energy E of ≈ 0.02 to ≈ 0.4 MeV/amu. If the three highest energy data points ($0.08 \leqslant E \leqslant 0.4$) are fitted with a power law in kinetic energy, the flux is given by $3.52 \times 10^{-4}\ E^{-(1.7^{+1.5}_{-0.6})}$ particles/cm²-sec-sr-MeV/amu with E in MeV/amu.

Another interesting result is obtained from the analysis of the lead phosphate (Lal) glass detectors. One detector was exposed directly to the Sun while the other was in the down-Sun direction. The track density in the Sun-exposed portion was 872 ± 134 tracks/cm², whereas the track density in the down-Sun or shaded portion was 430 ± 67 tracks/cm².

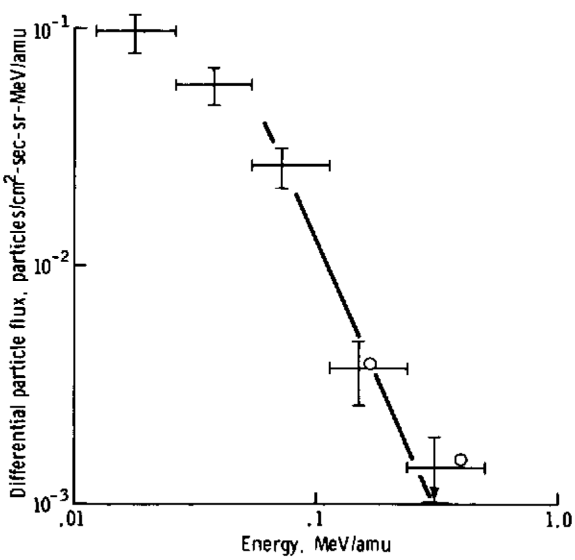

FIGURE 19-13.—Differential energy spectrum of heavy cosmic ray nuclei at the Moon from December 11 to 13, 1972, inferred from the distribution of stopping depths in phosphate glass (GE-1457). The two points marked by circles are the lowest energy data taken from the work of Price and Chan (part C, fig. 19-14).

TABLE 19-IV.—*Track Data in the Apollo 17 GE-1457 Phosphate Glass*

Particle range interval, cm	*Number stopping*	*Energy interval, MeV/amu* (a)	*Differential flux J, particles/cm²-sec-sr-MeV/amu* (b)
0.5 to 0.85 $\times 10^{-4}$	31	0.0121 to 0.0255	$9.56 \pm 0.17 \times 10^{-2}$
.85 to 1.43	38	0.0255 to 0.0537	$5.66 \pm 0.92 \times 10^{-2}$
1.43 to 2.41	37	0.0537 to 0.1130	$2.66 \pm 0.43 \times 10^{-2}$
2.41 to 4.05	11	0.1130 to 0.2370	$3.73 \pm 1.12 \times 10^{-3}$
4.05 to 6.85	9 (6)[c]	0.2370 to 0.5000	$1.44 \pm 0.48 \times 10^{-3}$

[a]Determined from range-energy tables (ref. 19-12).

[b]For this detector: exposure time = 45.5 hr; effective solid angle = 1.55 sr; area scanned = 9.38×10^{-2} cm²; index of refraction = 1.52; $J = (N/\Delta E)\ 4.2 \times 10^{-5}$ particles/cm²-sec-sr-MeV/amu, where N is track density and ΔE is difference in energy.

[c]The number in parentheses is the number of tracks that have not rounded. This means the particle stopped at a depth in the glass greater than the measured length of the track. It was assumed that some of the six sharp tracks in the length interval 4.05 to 6.85×10^{-4} cm could round out in the next larger length interval, hence the arrow on the highest energy data point in figure 19-13.

DISCUSSION

The glass-detector results show, at the higher energies ($0.05 \leq E$ (MeV/amu) ≤ 0.5), a steep spectral shape that can be fitted by a power law in kinetic energy: $6.33 \times 10^{-5}\ E^{-(2.3\,^{+1.2}_{-0.9})}$. At lower energies, the spectrum flattens. Qualitatively, the shape of the spectrum at higher energies is similar to that measured for single solar flare events (refs. 19-2 to 19-5 and 19-13, the first four references referring to analysis of the April 17, 1972, solar flare observed by the Apollo 16 cosmic ray experiment). The spectral shape at higher energies is also qualitatively similar to that observed for the cumulative effect of many flares over 2.5 yr at a time of maximum solar activity (refs. 19-14 to 19-16). This aspect alone suggests a solar origin for these low-energy, heavy cosmic rays. The absolute flux level at any given energy is much lower in the Apollo 17 spectrum than in the Apollo 16 spectrum. This is consistent with the satellite monitors, which showed orders of magnitude more protons during the Apollo 16 experiment than during the Apollo 17 experiment. A significant fact is that steep spectra are observed in both experiments even though solar modulation has presumably changed between these events.

The spectral character of the heavy particles seen (fig. 19-13) implies that they are solar in origin. It must now be determined whether our knowledge of the actual solar activity allows an understanding of the presence of heavy solar particles.

To begin, one must determine what solar activity is and how it is assessed. In December 1972, the overall solar activity based on the plot of smoothed sunspot number as a function of time[1] (ref. 19-17) was ≈40 percent of that at solar maximum as compared with 5 to 10 percent at full solar minimum. Consequently, the Sun was not totally quiet on the basis of this definition. On a shorter time scale, flares that do eject particles are closely correlated spatially with sunspot groups (ref. 19-18). The relation of satellite monitor data to the actual presence of particles depends on the sensitivity of the detectors. As satellite particle detectors become more sensitive, the percentage of flares that are observed to generate energetic particles increases. This suggests the following working hypothesis: the generation of energetic particles is a normal feature of all solar flares. Some flares may be more prolific generators than others, however (ref. 19-19). Also, satellite data indicate that X-rays and protons are generated almost continuously from active regions on the Sun. These observations imply that a highly efficient, nonthermal mechanism must be operative nearly all the time. Flares may be the obvious, large-scale phenomena, whereas the slowly varying emission may be the result

[1]H. I. Leighton and J. V. Lincoln, personal communication, 1973.

of the superposition of large numbers of microflares (ref. 19-20). In support of this idea, a plot of the number of flares as a function of their areas shows an increasingly greater number of small flares (ref. 19-18).

As an example of the abundance of small flares, during the period December 10 to 13, 1972 (the actual Apollo 17 experiment occurred in the period December 11 to 13), the following were observed: 11 sunspot groups; 52 flares of subflare category (on an S, 1, 2, 3, 4 level of classification of the Sun area involved, with faint (F), normal (N), and brilliant (B) associated with each level); one flare of importance 1F; and three radio bursts (ref. 19-17).

Because the GE-1457 glass detector was exposed facing away from the Sun, the inferred solar origin of the particles implies that, farther out in the solar system than the Earth-Moon distance, magnetic irregularities exist that effectively enable the detector to record heavy ions even though it faces away from the Sun. It is important to note that the two lead phosphate (Lal) glass detectors showed a difference in track densities, namely a larger track density in the Sun-exposed portion by a factor of 2. This difference makes clear the solar origin for the particles.

It is also of interest to consider the relative abundance of heavy elements during the period of this experiment. From the satellite proton flux and the heavy-element flux observed by the investigators, a value of the ratio of protons to heavy nuclei of ≈10 000 at 0.3 MeV/amu and a limit of < 10 000 at 1 MeV/amu can be derived. By comparison, values of 1200 and 12 000, respectively, were observed during the April 17, 1972, flare (ref. 19-4). In short, the heavy-element enrichment relative to protons observed in a flare is seen here also.

SUMMARY

Glass track detectors were exposed to cosmic rays on the Moon from December 11 to 13, 1972, during a period of relatively quiet Sun activity as inferred from satellite proton counters. From 80 to 400 keV/amu, the differential flux of heavy cosmic ray nuclei decreases roughly as E^{-2}; this result together with the greater flux from the solar than the antisolar direction identify these nuclei as solar in origin.

ACKNOWLEDGMENTS

The authors thank R. M. Walker and E. Zinner, who oversaw the construction, testing, and deployment of the experiment; Ian Palmer of Los Alamos Scientific Laboratories for proton information from the Vela satellite; and W. R. Giard, J. F. Norton, and L. J. Boudreaux of General Electric Research and Development Center for experimental assistance. We owe special thanks to D. Lal of Physical Research Laboratory, Navrangpura, Ahmedabad, India, for supplying samples of a new lead phosphate glass for use in this experiment.

PART C

THE NATURE OF INTERPLANETARY HEAVY IONS WITH $0.1 < E < 40$ MeV/NUCLEON

P. B. Price[a] *and J. H. Chan*[a]

The University of California cosmic ray detector was a stack of seven sheets of Lexan, each 125 μm thick and 3.5 by 4.5 cm in size, that was placed in the shade facing away from the Sun. The top sheet was coated with an ≈ 100-nm-thick layer of aluminum to screen out ultraviolet light, which would increase the sensitivity to particle tracks in an undesirable way.

In a preliminary examination of 1-cm² portions from the top, middle, and bottom of the stack, two distinct populations of particles that entered the stack from the antisolar direction were discovered: (1) particles with a steeply falling energy spectrum, the overwhelming majority of which penetrated less than ≈ 40 μm into the top sheet, and (2) a very low flux of particles with ranges distributed apparently uniformly throughout all seven sheets. Evidence is

[a]University of California at Berkeley.

presented that the first group was of solar origin, even though the Sun was relatively quiet during the 45.5-hr exposure of the cosmic ray detectors, and that the second group consisted of galactic cosmic rays with a fairly flat energy spectrum.

SUPRATHERMAL IONS OF SOLAR ORIGIN

To study the population of interplanetary particles with a steeply falling energy spectrum, small portions of the top sheet are etched for short times, tracks on the top surface are located and measured, the surface is irradiated with ultraviolet light to increase the etching rate greatly, and, finally, the surface is re-etched to determine the total ranges of the particles. The initial and final lengths of each track are two parameters that allow charge Z and energy E to be determined. The minimum energy for which charge determination is possible is determined by the track length after the first etch.

The data obtained thus far are shown in figure 19-14. The energy spectra of the various species appear to have rather similar shapes, within the limited statistics. To facilitate a comparison, the spectrum of the carbon-nitrogen-oxygen (CNO) group

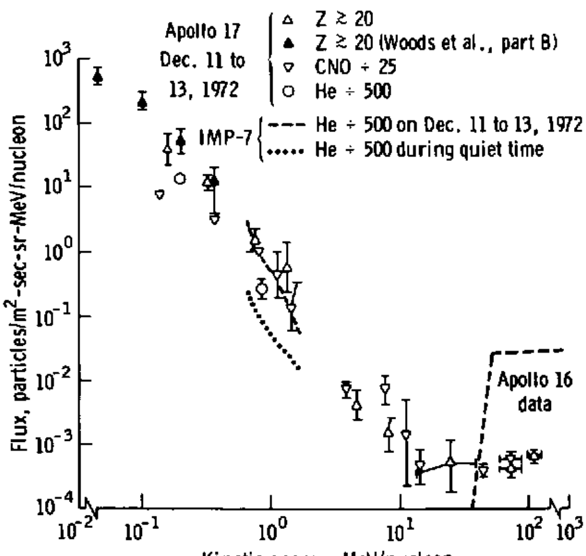

FIGURE 19-14.—Energy-dependent composition of low-energy interplanetary ions during solar quiet time. To display the enhancement of heavy elements at low energies, the fluxes of CNO and He have been scaled down by their abundances relative to Fe in the Sun. The enhancement appears to disappear at energies greater than ≈ 1 MeV/nucleon.

has been scaled downward by a factor of 25 and the helium (He) spectrum has been scaled downward by a factor of 500. The data then fall reasonably close to a single power law showing no strong dependence of composition on energy. The magnitudes of the ratios $Z \geqslant 20$:CNO:He $\approx$ 1:25:500 are quite different from the solar photospheric ratios, which are approximately 1:50:3000. The heavy elements are thus more abundant in the energetic particles than in the Sun. The flux of He ions measured in the Lexan stack agrees reasonably well with the flux determined by electronic detectors on IMP-7, shown as a dashed line. During the time of exposure of the plastics, the He flux was about five times higher than its minimum value, shown as a dotted line, corresponding to a solar "quiet time." The shapes of the energy spectra are not a convincing proof that the particles observed during the Apollo 17 mission were of solar origin. To provide additional evidence, we measured the relative abundance of C, N, and O at an energy of $\approx$ 3.9 MeV/nucleon. The result is that O:C+N $\approx$ 1.65, which is indistinguishable from the solar abundance ratio ($\approx$ 1.67) and much higher than that for galactic cosmic rays ($\approx$ 0.74) and strongly suggests that the majority of the particles are solar in origin. Presumably they were scattered from magnetic field irregularities in interplanetary space until their directions of motion were isotropic and entered the detector from all directions.

In the upper part of figure 19-15, measurements of solar Fe fluxes during the Apollo 17, Apollo 12 (ref. 19-22), and Apollo 16 (ref. 19-5) missions are compared with the long-term average interplanetary Fe flux based on measurements of tracks accumulated in the Surveyor III camera glass during 1967 to 1970 by the investigators (ref. 19-16), by Fleischer et al. (ref. 19-14), and by Crozaz and Walker (ref. 19-15). It is seen that, even during a solar quiet time, objects on planetary surfaces and in interplanetary space are being irradiated with ions as heavy as Fe (Z = 26) and of mean energy on the order of 0.1 MeV/nucleon. The long-term contribution during solar quiet times is, however, inconsequential in comparison with the contribution from occasional intense solar flares. Most of the tracks that accumulated in the Surveyor III glass during a 2.6-yr period probably came during seven major flares, each lasting 1 to 2 days.

The discovery of heavy-particle enhancements in solar flares (ref. 19-16) was an unexpected dividend of the Apollo Program. Results of the present

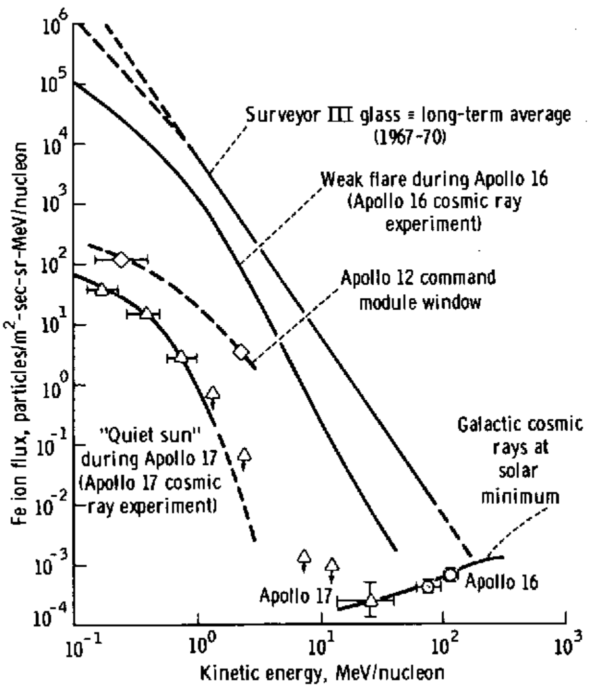

FIGURE 19-15.–Flux of Fe ions in space. The points labeled 16 and 17 are measurements of the galactic cosmic rays in the plastic-detector experiments on the Apollo 16 and 17 missions. For ≈ 24 hr during the Apollo 16 mission, a weak flare produced an Fe ion flux ≈ 10 percent of the long-term average observed in the Surveyor III glass. During the Apollo 12 and 17 missions, the Fe ion flux was negligible by comparison. Clearly, the major contribution to the long-term average would be from occasional very intense solar flares.

experiment, together with those of studies of solar particle composition using plastic detectors on the Apollo 16 mission and in rocket flights (summarized in ref. 19-23), provide important clues to the mechanisms of solar particle emission. In this preliminary report, the emission mechanisms are not discussed, but the clues are summarized as follows.

1. At sufficiently low energies, heavy elements in solar flare particles are always enriched relative to their photospheric abundances.

2. The enrichment factor $Q \equiv (Z/\text{He})_{SP}/(Z/\text{He})_{\theta}$ is an increasing function of Z from He at least up to $Z \approx 40$ (ref. 19-24). The subscripts SP and θ refer to abundance ratios in solar particles and in the Sun, respectively. Because only the elements He, O, silicon (Si), Fe, $32 \leqslant Z \leqslant 38$, and $Z > 40$ have thus far been studied, a possible fine structure in the enrichments such as a correlation with ionization potential cannot be ruled out yet.

3. The enrichment factor decreases with energy and approaches a constant value at some characteristic energy on the order of the mean energy of the flare particles.

4. The mean energy, defined as $\int \phi(E) E dE / \int \phi(E) dE$, with $\phi(E)$ denoting the energy spectrum, appears to be an increasing function of the intensity of the flare, ranging from $\lesssim 1$ MeV/nucleon for the quiet Sun to ≈ 8 MeV/nucleon for the very intense flare on August 4, 1972 (ref. 19-21).

5. The maximum value of the enrichment factor (observed at the lowest energy accessible with the Lexan detector, ≈ 0.1 MeV/nucleon) is similar for all solar conditions, ranging from quiet Sun to the most intense flare.

6. Even at energies as low as ≈ 2 MeV/nucleon, solar flare Fe particles seem to be nearly completely ionized. The evidence is based on the shapes of differential rigidity spectra of He, O, and Fe (ref. 19-5) and on the minimum particle energies observed with rockets launched at Fort Churchill in Canada (ref. 19-25). Conditions at the accelerating region must be such as to remove even the inner electrons with ionization potentials of several keV. Once the particles are ionized, the amount of matter traversed between the solar atmosphere and the Moon is too little for the stripped heavy ion to reach charge equilibrium by electron capture.

LOW-ENERGY GALACTIC COSMIC RAYS

Half of each sheet in the Lexan stack has been etched 72 hr in a 6.25N sodium hydroxide solution saturated in Lexan etch products. Each sheet has been scanned in a stereomicroscope for tracks of cosmic rays with $Z \geqslant 14$. Cone length and residual range of particle tracks that are estimated on the basis of previous experience (ref. 19-26) to have $Z \gtrsim 20$ have been measured.

Tracks of particles with $Z \gtrsim 14$ observed in one-half the stack are listed in table 19-V. A sizable background of unwanted particles is immediately apparent. Seven of the 24 particles entered the sheets through the back of the detector. Although some may have reached the detector in a direct path between the legs and under the body of the lunar module, the solid angle for such paths is small. It is possible that such events occurred during the approximately 10 days when the detector was inside the spacecraft in transit to and from the Moon. Of the 17 particles that entered the detector from the front, six

TABLE 19-V.—*Cosmic Ray Tracks of Particles with Z ⩾ 14 in One-Half the Stack*

Sheet in which particle stopped	Direction from which particle entered	Z
7	Front; sky	14
5	Back; sky	14
7	Front; Moon	20
6	Back; sky	18
7	Front; sky	14
< 1	Back; Moon	26
1	Back; Moon	26
> 7	Front; sky	26
6	Back; sky	20
> 7	Front; Moon	26
6	Front; sky	20
> 7	Front; sky	26
> 7	Front; sky	26
5	Front; Moon	18
4	Front; sky	20
5	Front; Moon	20
2	Back; sky	16
4	Front; sky	14
4	Front; sky	18
4	Front; Moon	18
3	Front; sky	22
2	Front; Moon	24
1	Back; Moon	14
2	Front; sky	14

apparently entered from below the horizon. It is difficult to see how this large fraction of the total could be attributed to cosmic ray albedo from the lunar surface. It is more likely that these particles, and a comparable number with acceptable directions (front; sky), actually entered the detector while it was inside the spacecraft. With no shifting mechanism such as was used on the Apollo 16 experiment, it is necessary to make approximate corrections for the fraction of unwanted particles with acceptable directions, based on the fraction with unacceptable directions.

In figures 19-14 and 19-15, a corrected flux of nuclei with $Z \gtrsim 23$ that stopped in the stack has been plotted. It was assumed that $17 - (2 \times 6) = 5$ particles entered the front of the detector during its approximately 45-hr lunar exposure. The energy interval is ≈ 11 to 39 MeV/nucleon. Two points at ≈ 70 and 120 MeV/nucleon from the Apollo 16 University of California detector (ref. 19-27) are included in figure 19-15. The statistics are such that we cannot be confident that the energy spectrum continues to drop with decreasing energy, but the trend is suggestive. When the other half of the stack is processed and analyzed, the statistical errors will decrease by $\approx \sqrt{2}$.

From the Z values in table 19-V, it is possible to assert with some confidence that the heavy nuclei in the energy interval 11 to 39 MeV/nucleon are of galactic rather than solar origin. The proportion of secondary nuclei with $17 \leqslant Z \leqslant 25$ relative to Fe is 11 to 6, which is too high for them to have come from the Sun.

From recent satellite measurements of the He flux in the same energy interval (ref. 19-28) and from abundance data at higher energy (summarized in ref. 19-29), we conclude that the abundance ratio He/Fe-group is independent of energy from ≈10 to ≈2000 MeV/nucleon. By using the previously described ultraviolet-sensitization and re-etch scheme, we shall be able to determine the fluxes of galactic CNO and He nuclei at energies of a few to ≈ 20 MeV/nucleon, an interval that has been largely unexplored until now.

CONCLUSIONS

Suprathermal ions with an energy spectrum that decreases by a factor of $\approx 1 \times 10^5$ in the interval 0.1 to ≈ 7 MeV/nucleon are believed to have been emitted by the Sun when it was relatively quiet. At very low energies, the Fe/CNO ratio and the CNO/He ratio are enhanced relative to their photospheric ratios at all energies studied (≈ 0.2 to ≈ 10 MeV/nucleon).

Particles with $14 \leqslant Z \leqslant 26$ were detected at energies between ≈ 10 and ≈ 40 MeV/nucleon. Their flux is slightly lower than the flux of such particles observed at energies of ≈ 60 to 150 MeV/nucleon on the Apollo 16 experiment. From their high abundance ratio of $17 \leqslant Z \leqslant 25$/Fe as well as their flux level, these particles are attributed to galactic cosmic rays. The abundance ratio of He/Fe appears to be independent of energy from ≈ 10 to ≈ 2000 MeV/nucleon.

ACKNOWLEDGMENTS

We thank Joan Steel and Dr. J. D. Sullivan of the University of California for their assistance in the preparation and calibration of the Lexan detectors.

REFERENCES

19-1. Fleischer, R. L.; and Hart, H. R., Jr.: Composition and Energy Spectra of Solar Cosmic Ray Nuclei. Sec. 15, Part A, of the Apollo 16 Preliminary Science Report. NASA SP-315, 1972.

19-2. Price, P. B.; Braddy, D.; O'Sullivan, D.; and Sullivan, J. D.: Composition of Interplanetary Particles at Energies From 0.1 to 150 MeV/Nucleon. Sec. 15, Part B, of the Apollo 16 Preliminary Science Report. NASA SP-315, 1972.

19-3. Burnett, D.; Hohenberg, C.; Maurette, M.; Monnin, M.; et al.: Solar Cosmic Ray, Solar Wind, Solar Flare, and Neutron Albedo Measurements. Sec. 15, Part C, of the Apollo 16 Preliminary Science Report. NASA SP-315, 1972.

19-4. Fleischer, R. L.; and Hart, H. R., Jr.: Enrichment of Heavy Nuclei in the 17 April 1972 Solar Flare. Phys. Rev. Letters, vol. 30, no. 1, Jan. 1, 1973, pp. 31-34.

19-5. Braddy, D.; Chan, J. H.; and Price, P. B.: Charge States and Energy-Dependent Composition of Solar-Flare Particles. Phys. Rev. Letters, vol. 30, no. 14, Apr. 2, 1973, pp. 669-671.

19-6. Natowitz, Joseph B.; Khodai-Joopari, Arastoo; Alexander, John M.; and Thomas, T. Darrah: Detection of Long-Range Fragments from Decay of Cf^{252}. Phys. Rev., vol. 169, no. 4, May 20, 1968, pp. 993-999.

19-7. Blok, H.; Kiely, F. M.; and Pate, B. D.: The Track Lengths of Heavy Ions in Mica. Nucl. Inst. Meth., vol. 100, no. 3, May 1, 1972, pp. 403-411.

19-8. Huang, W. H.; and Walker, R. M.: Fossil Alpha-Particle Recoil Tracks: A New Method of Age Determination. Science, vol. 155, no. 3715, Mar. 3, 1967, pp. 1103-1106.

19-9. Gorenstein, Paul; and Bjorkholm, Paul: Detection of Radon Emanation from the Crater Aristarchus by the Apollo 15 Alpha Particle Spectrometer. Science, vol. 179, no. 4075, Feb. 23, 1973, pp. 792-794.

19-10. Turkevich, Anthony L.; Patterson, James H.; Franzgrote, Ernest J.; Sowinski, Kenneth P.; et al.: Alpha Radioactivity of the Lunar Surface at the Landing Sites of Surveyors 5, 6, and 7. Science, vol. 167, no. 3926, Mar. 27, 1970, pp. 1722-1724.

19-11. Biswas, S.; and Fichtel, C. E.: Composition of Solar Cosmic Rays. Space Sci. Rev., vol. 4, no. 1, 1965, pp. 709-736.

19-12. Northcliffe, L. C.; and Schilling, R. F.: Range and Stopping Power Tables for Heavy Ions, Texas A&M (College Station), 1970; Nuclear Data Tables, vol. 7, 1970, p. 233ff.

19-13. Lin, R. P.; Kahler, S. W.; and Roelof, E. C.: Solar Flare Injection and Propagation of Low-Energy Protons and Electrons in the Event of 7-9 July, 1966. Solar Phys., vol. 4, no. 1, 1968, pp. 338-360.

19-14. Fleischer, R. L.; Hart, H. R., Jr.; and Comstock, G. M.: Very Heavy Solar Cosmic Rays: Energy Spectrum and Implications for Lunar Erosion. Science, vol. 171, no. 3977, Mar. 26, 1971, pp. 1240-1242.

19-15. Crozaz, G.; and Walker, R. M.: Solar Particle Tracks in Glass from the Surveyor 3 Spacecraft. Science, vol. 171, no. 3977, Mar. 26, 1971, pp. 1237-1239.

19-16. Price, P. B.; Hutcheon, I.; Cowsik, R.; and Barber, D. J.: Enhanced Emission of Iron Nuclei in Solar Flares. Phys. Rev. Letters, vol. 26, no. 15, Apr. 12, 1971, pp. 916-919.

19-17. Leighton, H. I.; and Lincoln, J. V., eds.: Solar Geophysical Data. World Data Center A for Solar-Terrestrial Physics, National Oceanic and Atmospheric Administration (Boulder, Colorado), no. 341, part 1, Jan. 1973.

19-18. Smith, Henry J.: Solar Flares: Their Structure, Development, and Motion. AAS-NASA Symposium on the Physics of Solar Flares. NASA SP-50, 1964, pp. 1-14.

19-19. McCracken, K. G.: High Energy Particle Events Associated with Solar Flares. Solar Flares and Space Research, North Holland Publishing Company (Amsterdam), 1969, pp. 202-214.

19-20. Friedman, H.: X-Ray Observations of Solar Flares. Solar Flares and Space Research, North Holland Publishing Company (Amsterdam), 1969, pp. 87-94.

19-21. Price, P. B.; Chan, J. H.; Crawford, H. J.; and Sullivan, J. D.: Systematics of Heavy Ion Enhancements in Solar Flares. Proceedings of the 13th International Cosmic Ray Conference (University of Denver), 1973.

19-22. Chan, J. H.; Price, P. B.; and Shirk, E. K.: Charge Composition and Energy Spectrum of Suprathermal Solar Particles. Proceedings of the 13th International Cosmic Ray Conference (University of Denver), 1973.

19-23. Price, P. B.; Chan, J. H.; Hutcheon, I. D.; Macdougall, D.; et al.: Low-Energy Heavy Ions in the Solar System. Proceedings of the Fourth Lunar Science Conference, Pergamon Press (New York), Dec. 1973.

19-24. Shirk, E. K.; and Price, P. B.: Observation of Trans-Iron Solar Flare Nuclei in an Apollo 16 Command Module Window. Proceedings of the 13th International Cosmic Ray Conference (University of Denver), 1973.

19-25. Sullivan, J. D.; and Price, P. B.: On the Charge State of Low-Energy Fe Nuclei Accelerated by Solar Flares. Proceedings of the 13th International Cosmic Ray Conference (University of Denver), 1973.

19-26. Price, P. B.; Fleischer, R. L.; Peterson, D. D.; O'Ceallaigh, C.; et al.: High-Resolution Study of Low-Energy Heavy Cosmic Rays with Lexan Track Detectors. Phys. Rev. Letters, vol. 21, no. 9, Aug. 26, 1968, pp. 630-633.

19-27. O'Sullivan, D.; Thompson, A.; and Price, P. B.; Composition of Galactic Cosmic Rays with $30 < E < 130$ MeV/N. Nature Physical Science, vol. 243, May 7, 1973, pp. 8-9.

19-28. Garcia-Munoz, M.; Mason, G. M.; and Simpson, J. A.: A New Test for Solar Modulation Theory: The May-July 1972 Low Energy Galactic Cosmic Ray Proton and Helium Spectra. Astrophys. J. Letters, vol. 182, 1973, pp. L81-L84.

19-29. Webber, W. R.; Lezniak, J. A.; Kish, J. C.; and Damle, S. V.: Evidence for Differences in the Energy Spectra of Cosmic Ray Nuclei. Nature Physical Science, vol. 241, no. 109, Jan. 29, 1973, pp. 96-98.

13th International Cosmic Ray Conference, Conference Papers, Vol. 2, University of Denver, 1973.

Title: Measurements of Extremely Low-Energy VH Ions in Space During a Flare and During "Quiet" Time Sun Conditions

Author(s): M. Maurette, R. Walker, and E. Zinner

Sponsoring Institution(s): Laboratory for Space Physics
Washington University

Postal address for author underlined above: St. Louis, Missouri 63130

Abstract

Mica, feldspar, and glass detectors flown during the Apollo 16 mission were exposed to a relatively minor solar flare. The density of VH tracks was extremely high ($\sim 10^6/cm^2$) and analysis of the track length distribution shows that the particle flux continues to increase with decreasing energy down to at least 15 kev/nuc. Above 200 kev/nuc the energy spectrum is describable as a power law. The Apollo 17 mission was flown at a time when there was an active area on the sun but no measurable particle or X-ray emissions. Mica detectors exposed during this time give track densities of $\sim 2 \times 10^3/cm^2$ for long ($\geq .2\mu$) tracks observable in normal optical microscopy. Phase contrast microscopy shows a wealth of shallow pits due predominantly to solar wind iron ions. The long tracks were observed in detectors placed in both the sun and the shade and have an energy spectrum similar to solar flare particles. These results show that interplanetary region is heavily populated with low-energy heavy ions. The implications of those results for track studies in lunar samples will be discussed.

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Lunar Science V, Lunar Sci. Inst., Houston, 1974.

APOLLO 17 LUNAR SURFACE COSMIC RAY EXPERIMENT - MEASUREMENT OF HEAVY SOLAR WIND PARTICLES, J. Borg and M. Maurette, Laboratoire René Bernas, Orsay, France, and R. M. Walker and E. Zinner, Laboratory for Space Physics, Washington University, St. Louis, Mo. 63130

The Apollo 17 Lunar Surface Cosmic Ray Experiment (LSCRE) consisted of a series of metal foils and nuclear track detectors designed to measure light and heavy solar wind particles as well as more energetic solar and galactic nuclei (Fig. 1). One half of the experiment was mounted in the sun and the other half in the shade for a total of 45.5 hours on the moon. During this time the flux of protons of energies > 3 MeV did not exceed that of quiet sun conditions. However, proton and He fluxes in the range of 0.3 to 1 MeV/nuc as measured on Vela (1), Pioneer 10 (2), and Imp 7 (2) were about a factor of 10 higher than normal quiet time levels during the second half of the period of deployment. We report here fluxes of solar wind particles based on an analysis of the mica detectors. Results for more energetic particles have previously been reported by us and the G. E. and Berkeley groups (3-7). The abundances given by the Berkeley group for particles with energies from 0.2 to 40 MeV/nuc indicate a mixture of solar and galactic particles.

Calibration Experiments: Heavy ions of solar wind energy (∿1 keV/nuc) produce shallow pits in etched mica (8). We used two different etching times and two methods of observation to study particles in different mass ranges. Samples etched for 10 min in a 40% HF solution at 30°C were studied using Pt-C replicas and a transmission electron microscope. Samples etched for 2 hrs were silvered and studied with an optical microscope using interference contrast in reflected light (Nomarski method for Zeiss microscopes). The shorter etching was used for the abundant lighter elements (CNO to Fe), the second for less abundant heavier masses. Calibration irradiations were made with 0.9 keV/nuc ions of O, Ne, Ar, and Fe at fluxes between $5 \times 10^8/cm^2$ and $5 \times 10^{11}/cm^2$. Pit size distributions and registration efficiencies were measured as a function of temperature to account for annealing on the moon and to separate charge groups by differential annealing. Pit sizes for all ions range from zero to a maximum of 0.8 microns after a 10 min etch. The pits produced by Fe ions are deeper than those produced by O and the former can clearly be separated from the latter. Fig. 2 shows the registration efficiencies applying two different acceptance criteria for pits. No difference in pit morphologies was found for Fe^+, Fe^{++}, and Fe^{+++} calibration ions. After 2 hrs etching, Kr, Xe, and Pb give pits that increase in average size with increasing mass (see Fig. 3). Calibration experiments show that the pit distributions for these heavier elements are modified by the presence of large numbers of lighter Fe ions. The lunar environment was simulated by studying the registration and annealing of heavy particles in samples that also contained 1.5×10^9 Fe ions/cm^2. As a function of annealing temperature, there is a flat maximum for the efficiency of detecting large pits at the presence of Fe background between 150°C and 200°C. Measurement of the registration of Mn, Kr, and Xe as a function of bombarding angle showed only small effects.

Abundance of Fe-Group Elements: The mica samples exposed in the sun had fifty times as many small pits as those exposed in the shade. Applying both scanning criteria (Fig. 2), we derive a flux of Fe group particles of $3.1 \pm 0.8 \times 10^4$/sec cm^2. Unfortunately, no satellite data of the proton solar wind are available for the same period. Assuming the average proton flux of 2.4×10^8/sec cm^2 (9), we obtain a Fe/H ratio of 1.28×10^{-4}. This value is subject to changes awaiting the still outstanding measurements of the light rare gas abundances from the metal foils. For the moment it exceeds the only other direct observation from a satellite of 3.45×10^{-5} (10) and the solar system abundances of 2.85×10^{-5} (11) by a factor of four. Taking into account our errors, we can rule out an overabundance of Fe in the solar wind by more than a factor of 5. Because of the extreme shallowness of oxygen pits and the large errors on the registration efficiencies, only a crude upper limit estimate can be made on the CNO abundance. We obtain a value of 1.2×10^6/sec cm^2 which is a factor of 4.3 above the solar system abundance (again assuming a proton flux of 2.4×10^8/sec cm^2).

Experimental Results on Large Pits: We previously reported a puzzling lack of large pits (3). We now understand that this is due to a combination of the suppression of large pits by the background of small ones and annealing effects on the moon. Our conclusions on the abundance of extremely heavy ions is limited by a background of pits produced by the more energetic particles that were present in the interplanetary medium during the mission. Calibration irradiations with Na, Ar, and Fe ions with energies up to 30 keV/nuc have shown that pits from such particles are very shallow and cannot in many cases be distinguished from solar wind pits. Fig. 4 shows the results of the analysis of sun and shade micas after a preannealing at 175°C. The background observed in the shade mica sets an upper limit on the heavy element abundances in the solar wind. We can rule out an overabundance of $Z > 45$ elements relative to Fe by more than a factor of ~ 7 and of $Z > 60$ of ~ 2.

REFERENCES

(1) I. D. Palmer, private communication.
(2) J. A. Simpson, private communication.
(3) Report 19, Cosmic Ray Experiment, by R. M. Walker et al, P. B. Price et al, and R. T. Woods et al, in the Apollo 17 Preliminary Science Report, NASA, 1973.
(4) R. T. Woods et al, 13th Intl. Cosmic Ray Conference, Conference Papers, Vol. 2, 1644, Denver, 1973.
(5) P. B. Price et al, ibid, Vol. 1, 146.
(6) J. H. Chan et al, ibid, Vol. 2, 1650.
(7) P. B. Price et al, ibid, Vol. 2, 1479.
(8) W. H. Huang and R. M. Walker, Science 155, 1103 (1967).
(9) A. J. Hundhausen, Rev. Geophys. and Space Physics 8, 729 (1970).
(10) S. J. Bame et al., J. Geophys. Res. 75, 6360 (1970).
(11) A. G. W. Cameron, Abundances of elements in the solar system, preprint.

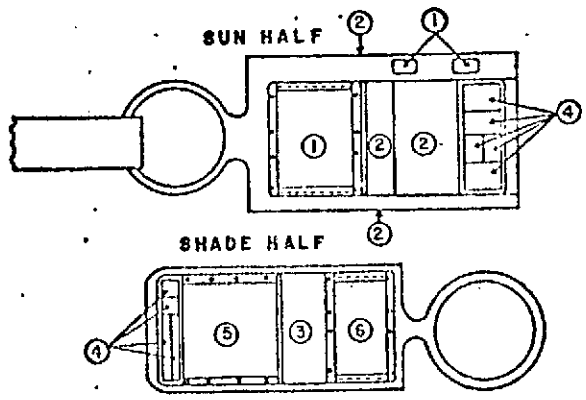

Fig. 1 Detectors of the Lunar Surface Cosmic Ray Experiment. #1 sun mica (heavy solar wind), #2 and #3 metal foils (#2 light solar wind, #3 for control), #4 glass detectors and #5 Lexan stack (more energetic particles of solar and galactic origin), #6 shade mica

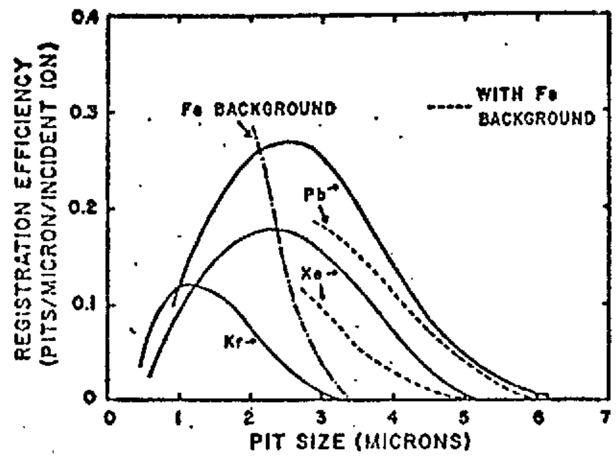

Fig. 3 Pit size distribution for Kr, Xe and Pb ions after annealing at 175°C for 72 hrs and etching for 2 hrs. The area under the curves gives the total registration efficiency. Increasing annealing temperatures result in decreasing average pit sizes and a reduction of registration efficiencies affecting lighter elements first (eg. annealing at 175°C reduces the total registration efficiency of Kr from 48% to 16% but that of Pb only from 90% to 80%). Also shown are the efficiencies for Xe and Pb registration in the presence of an Fe background of 1.5 x 10^9 ions/cm^2.

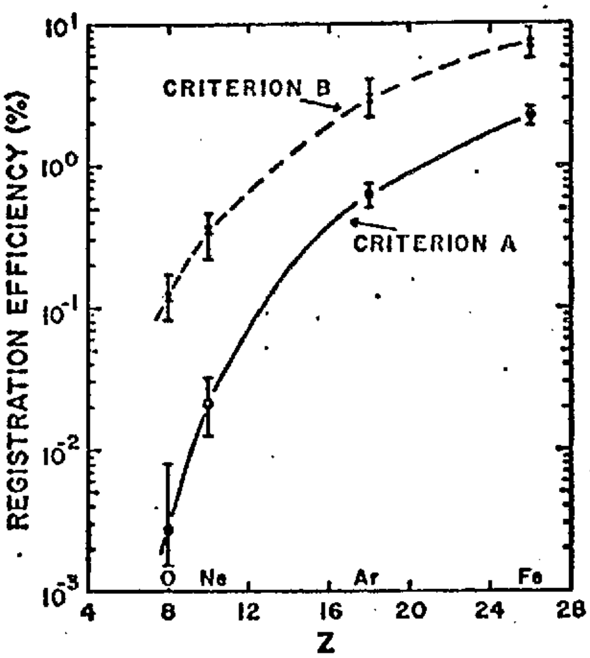

Fig. 2 Registration efficiencies of various ions of 0.9 keV/nuc energy after annealing at 120°C and etching for 10 min. Two different (arbitrary) criteria have been applied for the acceptance of pits, criterion A accepting pits beyond a certain apparent depth, criterion B accepting also shallower pits.

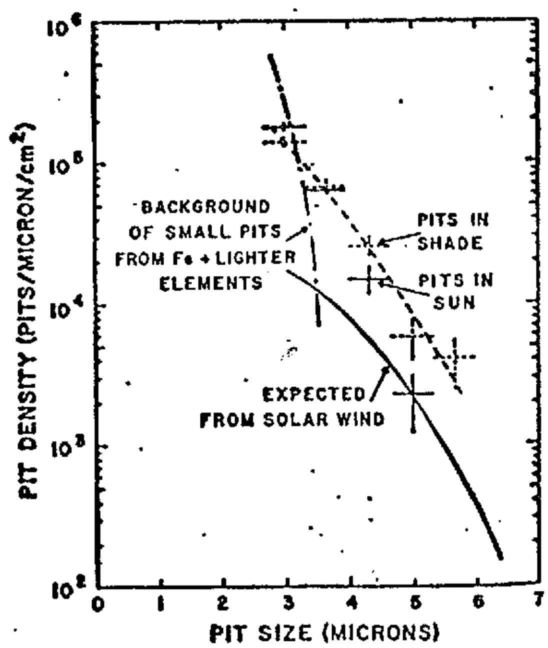

Fig. 4 Pit size distribution of large pits in sun and shade after annealing at 175°C and etching for 2 hrs. Plotted are pit sizes larger than those of the Fe group background. Shown also is the pit size distribution expected from heavy solar wind particles based on our Fe group flux and assuming solar system abundances (11).

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APOLLO 17 LUNAR SURFACE COSMIC RAY EXPERIMENT - MEASUREMENT OF HEAVY SOLAR WIND PARTICLES

E. Zinner and R. M. Walker
Laboratory for Space Physics,
Washington University
St. Louis, Missouri 63130

and

J. Borg and M. Maurette
Laboratoire René Bernas,
Orsay, France

ABSTRACT

During the Apollo 17 mission a series of metal foils and nuclear track detectors were exposed both in the sun and in the shade on the surface of the moon. Here we give the analysis of the mica detectors which were used to measure the flux of solar wind particles of Fe-group and heavier elements. These particles register as shallow pits after etching in hydrofluoric acid. Calibration experiments were performed to determine the registration properties of different ions and to simulate the lunar environment. We obtain an Fe-group flux of $3.9 \times 10^4/\mathrm{sec\ cm}^2$, which together with the H flux measured on IMP-7 gives an Fe/H ratio of 4.1×10^{-5}. For elements with $Z > 45$ we can set only an upper limit on the abundance, ruling out an overabundance of extremely heavy elements relative to iron by a factor of 4.

INTRODUCTION

The energies, fluxes, and relative abundances of the elements in the solar wind contain information about the composition of the solar corona and the acceleration mechanisms for solar wind ions. In the last few years three methods of investigation have been used to study the solar wind. First, experiments using electrostatic analyzers flown on satellites have provided a direct measurement of light elements, mostly H and He (Bame, 1972). In a few very quiet periods, abundances of O, Si, and Fe have also been measured (Bame et al., 1970, 1974). Secondly, the Solar Wind Composition experiments on Apollo 11-Apollo 16 (Geiss et al., 1972) have used metal foils to measure the elemental and isotopic abundances of light rare gases in the solar wind. Third, the analysis of solar wind implanted ions in lunar samples has provided indirect measurements of the abundances of the rare gases up to xenon (Geiss, 1973). Because of heavy diffusion losses and other secondary processes on the lunar surface, lighter elements are systematically depleted, which makes a determination of elemental abundances difficult if not impossible. On the basis of the available data (Eberhardt et al.,1972), a possible overabundance of heavy elements ($\geq$ Xe) cannot be ruled out. One of the objectives of the Apollo 17 Lunar Surface Cosmic Ray Experiment (LSCRE) was a direct measurement of heavy solar wind particles.

DESCRIPTION OF EXPERIMENT

The Apollo 17 LSCRE consisted of a series of metal foils and nuclear track detectors mounted in the recesses of two flat aluminum pieces

(Fig. 1). Both halves of the experiment were deployed on the moon, one exposed to the sun, the other one in the shade. The experiment objectives were to measure 1) the flux of heavy solar wind ions by using mica detectors, 2) light noble gases in the solar wind with metal foils in a fashion similar to the previous Apollo SWC experiments, and 3) the flux of more energetic nuclei of solar and (possibly) galactic origin. A similar, larger and more elaborate experiment was flown on the Apollo 16 mission. Although the occurrence of a solar flare during that mission provided important solar flare data (Burnett et al., 1972; Fleischer and Hart, 1972, 1973; Price et al., 1972; Braddy et al., 1973), the high track background produced by the flare particles precluded measurement of solar wind effects.

DEPLOYMENT

The LSCRE was deployed on the lunar module from the beginning of the first EVA (1:23 UT, Dec. 12, 1972) to the end of the third EVA (22:53 UT, Dec. 13) for a total time of 45.5 hours. During this period the flux of protons with energies > 3 MeV did not exceed that of quiet sun conditions. However, proton and He fluxes in the range of 29 keV/nuc to 1.8 MeV/nuc as measured on IMP-6 (R. P. Lin, private communication), Vela 6A (I. D. Palmer, private communication), IMP-7 (J. A. Simpson, private communication) rose to levels more than a factor of 10 higher than typical quiet time counts during the second half of the period of deployment. Figure 2 shows the sudden increase in particle fluxes at the beginning of Dec. 13. Since only minor subflares were observed in the days before Dec. 13, it is not clear which solar event is associated with this enhancement. Data from Pioneer 10 (J. A. Simpson, private communication), then at 3.3 AU, for protons and alphas in the energy range from 0.5 to 1.8 MeV/nuc show an enhancement by a factor of 3 to 5 on both days and indicate that this time was a non-quiet period. After return from the moon, different detectors were analyzed by different groups. Results for particles in the energy range from 0.02 to 40 MeV/nuc have been reported by us (Walker et al., 1973) (mica detectors), the G. E. group (Woods et al., 1973a, 1973b) (glass detectors), and the University of California, Berkeley group (Chan et al., 1973; Price and Chan, 1973; Price et al., 1973a, 1973b) (Lexan stack). The chemical abundances of He, CNO, and Fe group nuclei with energies between 0.2 and 40 MeV/nuc obtained by the last group indicate that in this energy range particles are of both solar and galactic origin. The metal foils are still being analyzed by the University of Berne group.

ANALYSIS OF MICA

Here we report fluxes of heavy solar wind particles based on the analysis of the mica detectors. Heavy ions of solar wind energy ($\sim$1 keV/nuc) produce shallow pits in mica after etching in hydrofluoric acid (Huang and Walker, 1967). Figure 3 shows a piece of mica from the sun half, a portion of which was covered by a steel strap holding the mica down. The picture was taken in an optical microscope after 2 hrs etching in

40% HF at 30°C. The effect of the solar wind ions on the surface exposed to the sun can be clearly seen. A separation of different mass groups is possible because the average etch pit size increases with the mass of the incident ions.

Four major problems made the analysis difficult and required careful calibration studies. The first problem was the great disparity between the flux of iron group particles (as well as lighter ions) and the flux of much heavier nuclei. The relatively small number of particles expected at higher atomic numbers ($\sim 10^4/cm^2$ with $Z > 70$) required the samples to be scanned at low magnification using optical microscopy. This in turn required long etch times. At such long etch times, pits produced by the abundant iron group particles overlap and can no longer be measured. The experiment was therefore divided into two parts: 1) a first etching of ten minutes followed by examination of the mica samples using Pt-C replicas and electron microscopy to measure the abundance of iron group particles (see Fig. 4), and 2) a second, longer etching of 2 hrs followed by optical observation of pits using interference microscopy in reflected light (Nomarski system for Zeiss microscopes) to measure the abundance of elements much heavier than iron.

At the long etching times used for the very heavy ion measurements, the overlap of smaller iron group pits produces a modification of the larger pits. Thus calibration experiments for the registration efficiency of heavy ions must be performed on samples that have also been irradiated with an appropriate number of iron ions.

Pits produced by low-energy ions in mica do not completely disappear even when the mica is heated to 300°C; nonetheless, noticeable annealing effects are produced by heating at temperatures as low as 120°C - the temperature attained by the LSCRE on the moon. The effects of such annealing must also be taken into account in the calibration work.

A final problem is a relatively large background of shallow pits caused by non-solar wind nuclear particles. These background pits are attributed by us to more energetic particles which were clearly present in the interplanetary medium during the time of exposure. Long tracks from these more energetic nuclei were seen in the mica (Walker et al., 1973) and also in Lexan and glass detectors (Chan et al., 1973; Price and Chan, 1973; Price et al., 1973a, 1973b; Woods et al., 1973a, 1973b). Calibration irradiations with Ne, Ar, and Fe ions with energies up to 30 keV/nuc show that some of these particles give incompletely etched tracks that result in pits that are shallow and that cannot be distinguished from heavy solar wind pits. This background gives the fundamental limitation on the conclusions that we are able to draw about heavy solar wind abundances.

CALIBRATION EXPERIMENTS AND THEIR RESULTS

a) Transmission electron microscope observations

Irradiations were made with 0.9 keV/nuc ions of O, Ne, Ar, and Fe at fluxes varying from $5 \times 10^8/cm^2$ to $5 \times 10^{11}/cm^2$. Pit size distributions and registration efficiencies were measured as a function of temperature to simulate the thermal conditions on the moon and to investigate the possibility of separating different mass groups by differential annealing. Pit sizes for all ions range from zero to a maximum of about 0.8 microns after a 10 min etch; neither the average width nor the size distribution exhibit a strong mass dependence. However, there is a marked mass dependence of the depth of pits; pits produced by Fe ions are deeper than those from O ions (see Fig. 5) and the former can be clearly distinguished from the latter. The effect of the application of depth criteria is demonstrated in Fig. 6 which shows the registration efficiencies of various ions after annealing at different temperatures. The fact that the efficiency for oxygen detection is far lower than that of iron means that most of the small pits are produced by ions of the Fe-group elements and not by the much more numerous CNO ions. All the other elements between CNO and the Fe group have such a small product of abundance times registration efficiency that their contributions can be neglected. Differential annealing did not provide a good method for mass separation since the proportional decrease in registration efficiency after annealing for 24 hrs at temperatures of up to 200°C was almost the same for different ions.

The elements in the solar wind are highly ionized. For example, Fe has been observed in charge states from +7 to +13 (Bame, 1972). All our calibration experiments were performed with singly charged ions except a series where we studied the effect of the charge state on the pit formation by comparing samples irradiated with Fe^{+}, Fe^{++}, and Fe^{+++} ions. No difference in registration efficiency, size, or depth was observed.

b) Optical microscope observation

After 2 hrs etching Kr, Xe, and Pb ions of 0.9 keV/nuc give pits that increase in average size with increasing mass (see Figs. 7 and 8). While early qualitative studies by us showed that large pits from heavy ions could be seen among a background of a large number of smaller pits from Fe group ions, quantitative calibration experiments show that the registration efficiencies and pit size distributions for these heavier elements are reduced by a large Fe background. This is demonstrated in Fig. 8 where we simulated the solar wind conditions by studying the registration of Kr, Xe, and Pb ions in calibration samples which were also irradiated with 1.5×10^9 Fe ions.

As shown in Fig. 9, heating of an irradiated sample reduces both the average size and the number of pits produced by subsequent etching. These heating effects are more pronounced for the lighter ions than for the heavier ions, e.g., annealing at 175°C for 72 hrs reduces the total registration efficiency for Kr by a factor of three while producing only a 10% reduction in the registration efficiency of Pb. This partial annealing provides a method for ameliorating the adverse effects of the large iron background. From curves such as shown in Fig. 10 we have found that annealing temperatures from 150°C to 200°C provide the optimum conditions for measuring the pits produced by ions much heavier than iron in the presence of a large iron background.

We also studied the dependence of registration efficiency and pit size on the angle of incidence for Mn, Kr, and Xe ions. Although both the efficiencies and the pit sizes increase with increasing angle, the effects are small, amounting to only a few percent for the increase in registration efficiency for angles up to 60° and about 6% for the increase in average pit size at 30° incidence. Since the solar wind was incident at angles < 25° from the perpendicular during exposure on the moon, the orientation effects play no role in our analysis.

RESULTS

a) Abundance of Fe-group elements

Portions of the mica samples irradiated respectively in sun and shade were analyzed by the replica plus transmission electron microscope technique. The mica exposed in the sun had fifty times as many small pits as the one exposed in the shade. The Fe-group flux in the solar wind was derived by analyzing a sun mica piece as returned from the moon and one pre-annealed for 24 hrs at 200°C. We obtain an average flux of Fe-group particles of $3.9 \pm 1 \times 10^4$/sec cm^2. To relate this value to the light rare gas fluxes, we still have to await the results of the analysis of the metal foils. However, as shown in Fig. 11, H and He solar wind fluxes were measured during this period on the IMP-7 satellite (W. C. Feldman, private communication). It can be seen that the second half shows disturbed conditions whose onset coincided with the sudden increase of higher energy particle counting rates (Fig. 2). The average solar wind values for the period during which the LSCRE was exposed are 8.9×10^8/cm^2 sec for the proton flux and 0.032 for the He/H ratio. Combining our Fe-flux result with this H-value gives an Fe/H ratio of 4.1×10^{-5}. Table 1 shows a comparison of our result with Vela results of the Los Alamos group (Bame et al., 1970, 1974) and with Cameron's solar system abundances (Cameron, 1973).

Table 1

Fe/H Ratios

Solar System[a]	2.61×10^{-5}
Vela 5A, 1969[b]	3.4×10^{-5}
Vela 5 and 6, average of 19 observations 1969-1971[c]	5.4×10^{-5}
Our result	4.1×10^{-5}

[a]Cameron, 1973

[b]Bame *et al*., 1970

[c]Bame *et al*., 1974

All experimental values are larger than the solar system abundance value. The satellite measurements were restricted to quiet periods, while our value represents a period of modest disturbance. There seems to be no essential difference in the Fe/H ratio for quiet and disturbed periods. It should be noted, however, that the value of 5.4×10^{-5} from the Vela 5 and 6 satellite experiments reported by Bame *et al*. constitutes an average from 19 distinct observations for which the Fe/H values vary over a range of ∿7. In view of these large variations, our value can be considered in good agreement with the solar system abundance. Any further conclusion about our results must wait for the results of the metal foil analysis of the light ions. However, it seems clear that in contrast to energetic, heavy solar particles in the energy range 10 keV/nuc <E<1 MeV/nuc (Chan and Price, 1974) there is no large systematic overabundance of Fe group elements in the solar wind.

Because of the extreme shallowness of oxygen pits and the large errors on the registration efficiencies, only a crude upper limit estimate can be made on the CNO abundance. We obtain a flux of 2.4×10^{6}/sec cm^{2}

and a corresponding CNO/H ratio of 2.7×10^{-3} which is 2.5 times the solar system value.

c) Experimental results on large pits

We previously reported a puzzling lack of large pits (Walker et al., 1973). We now understand that this is due to a combination of the suppression of large pits by the background of small ones and the annealing effects on the moon. Figure 12 shows the results of the analysis of sun and shade micas without any pre-annealing. There is a larger number of pits in the shade, but, given the same background in shade and sun, that is expected due to the suppression effect produced by the large background of iron group pits in the sun mica. This is shown by the fact that the ratio of the number of large pits in sun and shade is the same as the ratio of the expected number of heavy solar wind pits in the sun with and without the reduction by the Fe-background (solid and dashed curves). The background observed in the shade mica sets an upper limit on the abundance of heavy elements in the solar wind. We can rule out an overabundance of $Z > 45$ elements relative to Fe by more than a factor of ~ 4. We obtain essentially the same result from an analysis after pre-annealing at 175°C (Fig. 13). The difference between sun and shade mica almost disappears. The larger gap between observed pits and pits expected from the solar wind as compared with the non-annealed sample is explained by different annealing characteristics of pits from higher energy particles compared to solar wind pits.

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REFERENCES

Bame S. J., Asbridge J. R., Hundhausen A. J., and Montgomery M. D. (1970) Solar wind ions: $^{56}Fe^{+8}$ to $^{56}Fe^{+12}$, $^{28}Si^{+7}$, $^{28}Si^{+8}$, $^{28}Si^{+9}$, and $^{16}O^{+6}$. J. Geophys. Res. 75, 6360-6365.

Bame S. J. (1972) Spacecraft observations of the solar wind composition. Solar Wind, Proc. of Conf. sponsored by NASA held March 21-26, 1971, at the Asilomar Conference Grounds, Pacific Grove, California, NASA SP-308, pp. 535-558.

Bame S. J., Asbridge J. R., Feldman W. C., Montgomery M. D., and Kearney P. D. (1974) Solar wind heavy ion abundances (abstract SS22). Transactions, Amer. Geophys. Union 55, 410.

Braddy D., Chan J. H., and Price P. B. (1973) Charge states and energy-dependent composition of solar-flare particles. Phys. Rev. Letters 30, 669-671.

Burnett D., Hohenberg C., Maurette M., Monnin M., Walker R., and Woolum D. (1972) Solar cosmic ray, solar wind, solar flare, and neutron albedo measurements. Apollo 16 Preliminary Science Report, NASA SP-315, pp. 15-19 to 15-32.

Cameron A. G. W. (1973) Abundances of the elements in the solar system. Space Sc. Reviews 15, 121-146.

Chan J. H., Price P. B., and Shirk E. K. (1973) Charge composition and energy spectrum of suprathermal solar particles. 13th International Cosmic Ray Conference, Conference Papers, Vol. 2, pp. 1650-1654. Univ. of Denver.

Chan J. H. and Price P. B. (1974) Anomalies in the composition of interplanetary heavy ions with 0.01<E<40 MeV/amu. Submitted to Astrophys. J. Letters.

Eberhardt P., Geiss J., Graf H., Grögler N., Mendia M. D., Mörgeli M., Schwaller H., Stettler A., Krähenbühl U., and von Gunten H. R. (1972) Trapped solar wind noble gases in Apollo 12 lunar fines 12001 and Apollo 11 breccia 10046. Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3, Vol. 2, pp. 1821-1856. MIT Press.

Fleischer R. L. and Hart H. R. Jr. (1972) Composition and energy spectra of solar cosmic ray nuclei. Apollo 16 Preliminary Science Report, NASA SP-315, pp. 15-2 to 15-11.

Fleischer R. L. and Hart H. R. Jr. (1973) Enrichment of heavy nuclei in the 17 April 1972 solar flare. Phys. Rev. Letters 30, 31-34.

Geiss J., Buehler F., Cerutti H., Eberhardt P., and Filleux Ch. (1972) Solar wind composition experiment. Apollo 16 Preliminary Science Report, NASA SP-315, pp. 14-1 to 14-10.

Geiss J. (1973) Abundances in the solar wind and some applications to astrophysics and geophysics. Proc. Leningrad Seminar "Solar Cosmic Rays and their Penetration into the Earth's Magnetosphere," Leningrad June 1973, to be published.

Huang W. H. and Walker R. M. (1967) Fossil alpha-particle recoil tracks: A new method of age determination. Science 155, 1103-1106.

Price P. B., Braddy D., O'Sullivan D., and Sullivan J. D. (1972) Composition of interplanetary particles at energies from 0.1 to 150 MeV/nucleon. Apollo 16 Preliminary Science Report, NASA SP-315, pp. 15-11 to 15-19.

Price P. B. and Chan J. H. (1973) The nature of interplanetary heavy ions with $0.1 < E < 40$ MeV/nucleon. Apollo 17 Preliminary Science Report, NASA SP-330, pp. 19-15 to 19-19.

Price P. B., Chan J. H., O'Sullivan D., and Thompson A. (1973a) Galactic heavy cosmic rays with $5 < E < 130$ MeV/nucleon. 13th International Cosmic Ray Conference, Conference Papers, Vol. 1, pp. 146-151. Univ. of Denver.

Price P. B., Chan J. H., Crawford H. J., and Sullivan J. D. (1973b) Systematics of heavy ion enhancements in solar flares. 13th International Cosmic Ray Conference, Conference Papers, Vol. 2, pp. 1479-1483. Univ. of Denver.

Walker R. M., Zinner E., and Maurette M. (1973) Measurements of heavy solar wind and higher energy solar particles during the Apollo 17 mission. Apollo 17 Preliminary Science Report, NASA SP-330, pp. 19-2 to 19-11.

Woods R. T., Hart H. R. Jr., and Fleischer R. L. (1973a) Quiet time energy spectra of heavy nuclei from 20 to 400 keV/amu. Apollo 17 Preliminary Science Report, NASA SP-330, pp. 19-11 to 19-15.

Woods R. T., Hart H. R. Jr., and Fleischer R. L. (1973b) Low energy, heavy cosmic ray nuclei during a solar quiet time. 13th International Cosmic Ray Conference, Conference Papers, Vol. 2, pp. 1644-1649. Univ. of Denver.

FIGURE CAPTIONS

Figure 1 Detectors of the Lunar Surface Cosmic Ray Experiment. #1 sun mica (heavy solar wind), #2 and #3 metal foils (#2 light solar wind, #3 for control), #4 glass detectors and #5 Lexan stack (more energetic particles), #6 shade mica.

Figure 2 High energy proton and alpha particle counting rates from three satellite detectors on IMP-6 (R. P. Lin, private communication), Vela 6A (I. D. Palmer, private communication), and IMP-7 (J. A. Simpson, private communication) during Dec. 12 and 13 (Universal Time), the period of LSCRE deployment. All three spacecrafts have geocentric orbits.

Figure 3 Mica surface from the portion exposed to the sun after 2 hrs etching in 40% HF at 30°C. The photograph was taken with a Zeiss optical microscope using interference contrast method (Nomarski). The right side of the picture was covered with a 0.5 mm thick steel strap.

Figure 4 Mica surface of sun portion after 10 min etching in 40% HF at 30°C. Shown is a picture of a platinum-carbon replica taken with a transmission electron microscope.

Figure 5 Pits from 0.9 keV/nuc oxygen (left) and iron (right) ions after annealing for 45.5 hrs at 120°C followed by 10 min etching in 40% HF at 30°C. Etching and microphotography conditions the same as for Fig. 4. The dose of the O ions is $7 \times 10^{10}/cm^2$, that of the Fe ions is $1.5 \times 10^9/cm^2$.

Figure 6 Registration efficiencies of various ions of 0.9 keV/nuc after annealing at various temperatures and etching for 10 min. In addition to 24 hrs at the indicated higher temperatures, all samples have been annealed for 45.5 hrs at 120°C prior to etching. Two different criteria have been applied for the acceptance of pits. Criterion A represents counting pits greater than a certain depth; with criterion B pits surpassing a minimum width are counted independent of depth.

Figure 7 Pit size distribution for 0.9 keV/nuc Kr, Xe, and Pb ions after annealing at 120°C for 45.5 hrs followed by 2 hrs etching in 40% HF at 30°C. The areas under the curves give the total registration efficiencies. Also shown are the pit sizes for Xe and Pb in the presence of an Fe background of $1.5 \times 10^9 ions/cm^2$.

Figure 8 Pits from 0.9 keV/nuc Xe (left) and Pb (right) ions after pre-annealing for 45.5 hrs at 120°C followed by 2 hrs etching in 40% HF at 30°C. Etching and microphotography conditions the same as for Fig. 3. The doses of both Xe and Pb ions were $10^7/cm^2$.

Figure 9 Pit size distribution for Pb ions in mica annealed for various times followed by 2 hrs etching in 40% HF at 30°C. All samples (except that labeled NO, which was not annealed) were first annealed at 120°C for 45.5 hrs, corresponding to the time-temperature profile seen by the mica detectors on the moon. Additional annealing times of 72 hrs were employed for the higher temperatures indicated.

Figure 10 Pit size distribution for Pb ions in the presence of an Fe background of 1.5 x 10^9 ions/cm^2 after annealing at different temperatures (same conditions as in Fig. 9).

Figure 11 Proton and He solar wind data from IMP-7 (W. C. Feldman, private communication) for the period of LSCRE deployment.

Figure 12 Pit size distribution of large pits in sun and shade after 2 hrs etching. Plotted are pit sizes larger than those of the Fe-group background. The solid line indicates the pit size distribution expected from heavy solar wind particles based on our Fe-group dose and assuming solar system abundances (Cameron, 1973) and taking into account the reduction in registration efficiency by the Fe-group background. For the dashed line this reduction is not taken into account.

Figure 13 Pit size distribution of large pits in sun and shade after pre-annealing at 175°C. The solid line indicates the pit size distribution expected from heavy solar wind particles based on our Fe-group dose and assuming solar system abundances (Cameron, 1973) and taking into account the reduction in registration efficiency by the Fe-group background. For the dashed line this reduction is not taken into account.

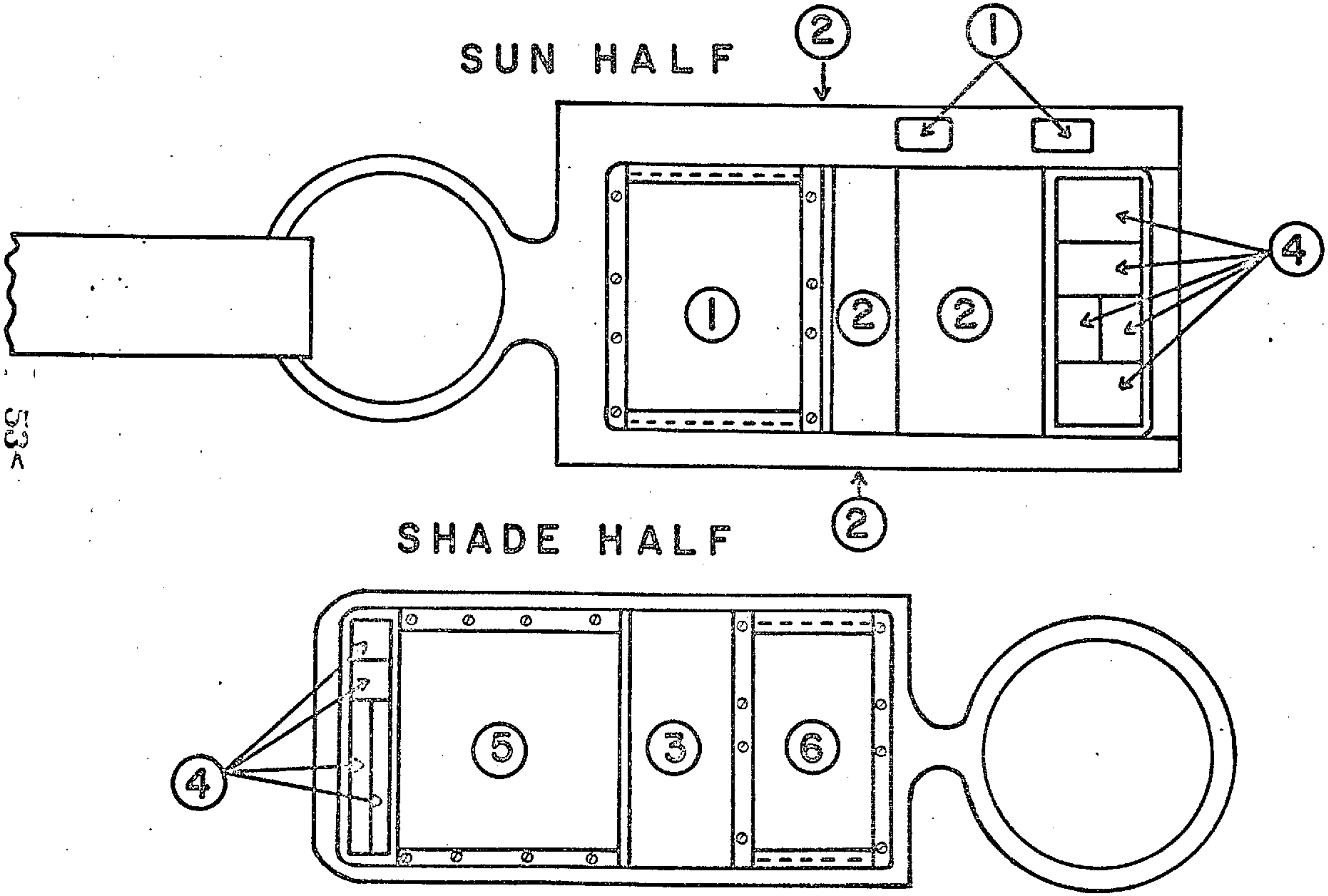
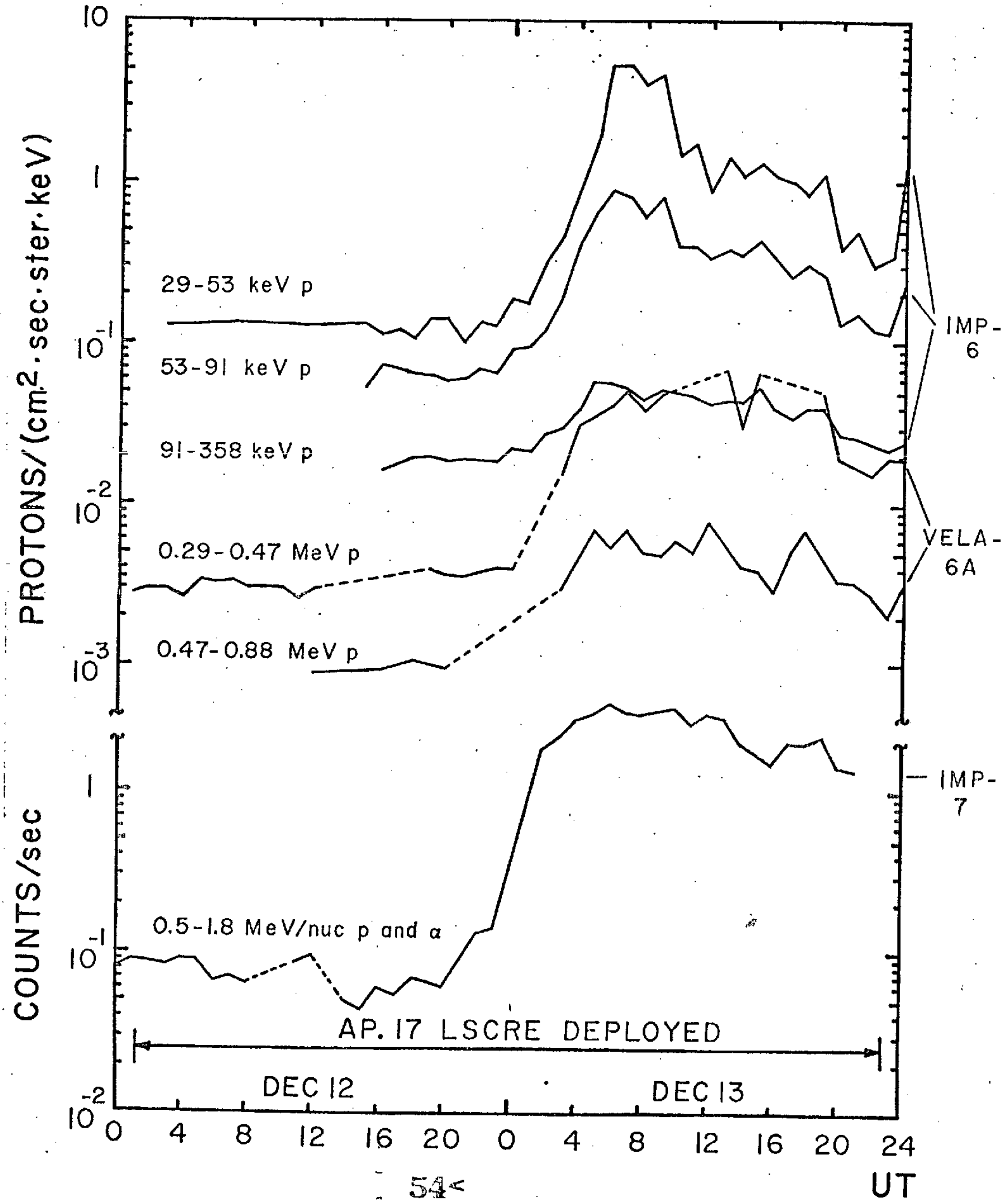


FIG. 1



PROTONS/(cm^2·sec·ster·keV)
10
1
10^{-1}
10^{-2}
10^{-3}
29-53 keV p
53-91 keV p
91-358 keV p
0.29-0.47 MeV p
0.47-0.88 MeV p
IMP-6
VELA-6A
COUNTS/sec
1
10^{-1}
10^{-2}
0.5-1.8 MeV/nuc p and α
IMP-7
AP. 17 LSCRE DEPLOYED
DEC 12
DEC 13
0 4 8 12 16 20 0 4 8 12 16 20 24
UT

FIG. 2

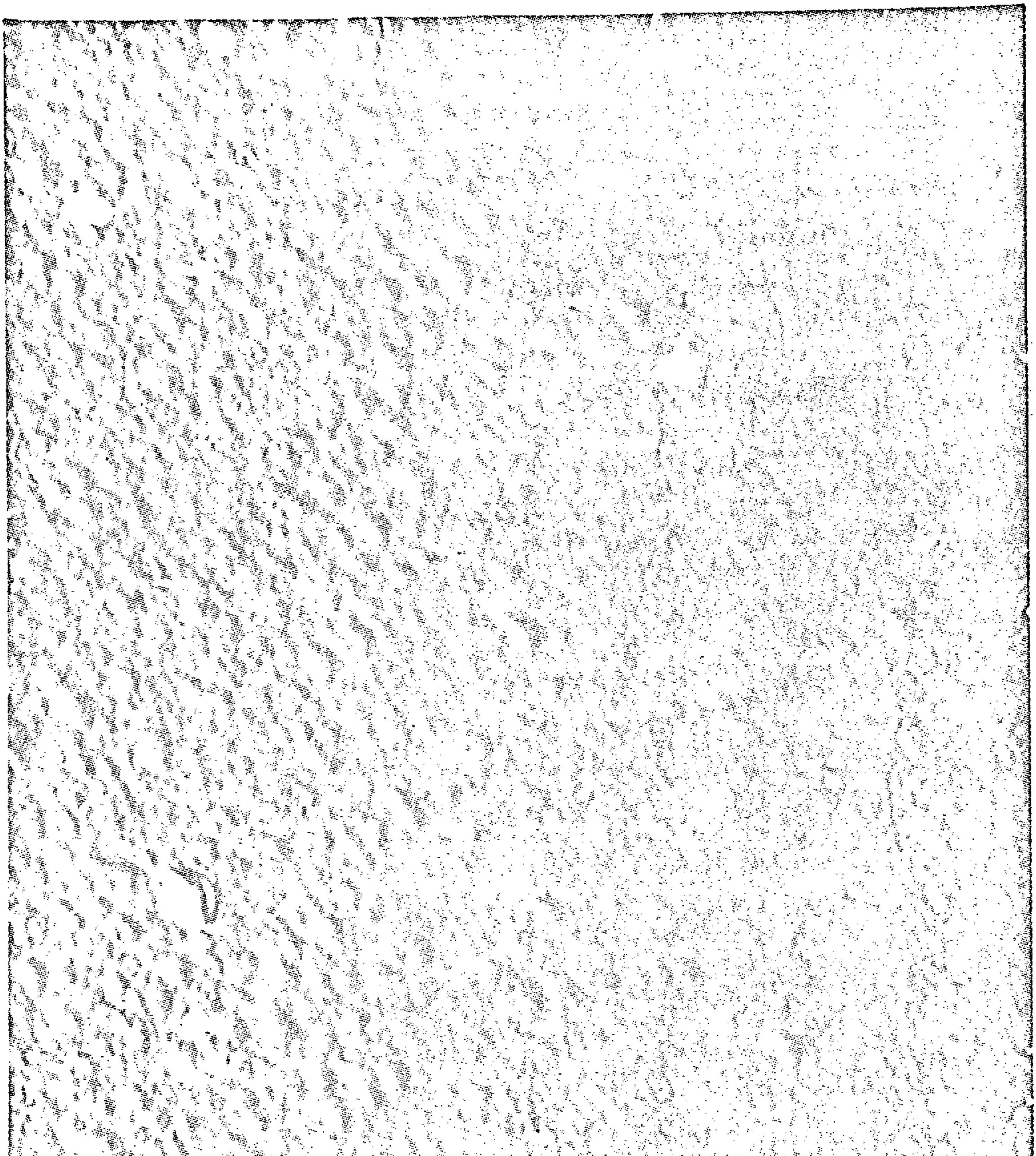


FIG. 3

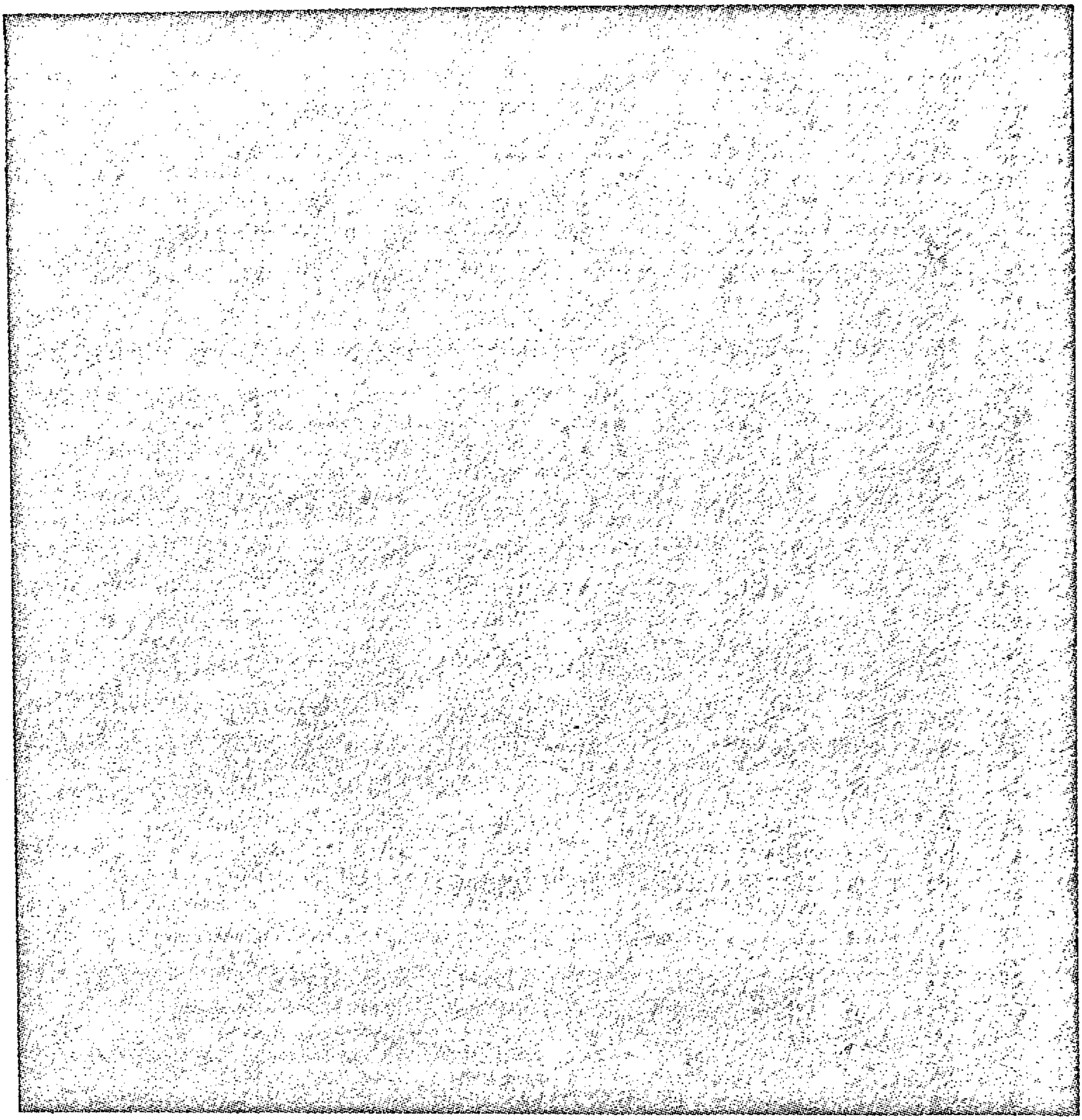
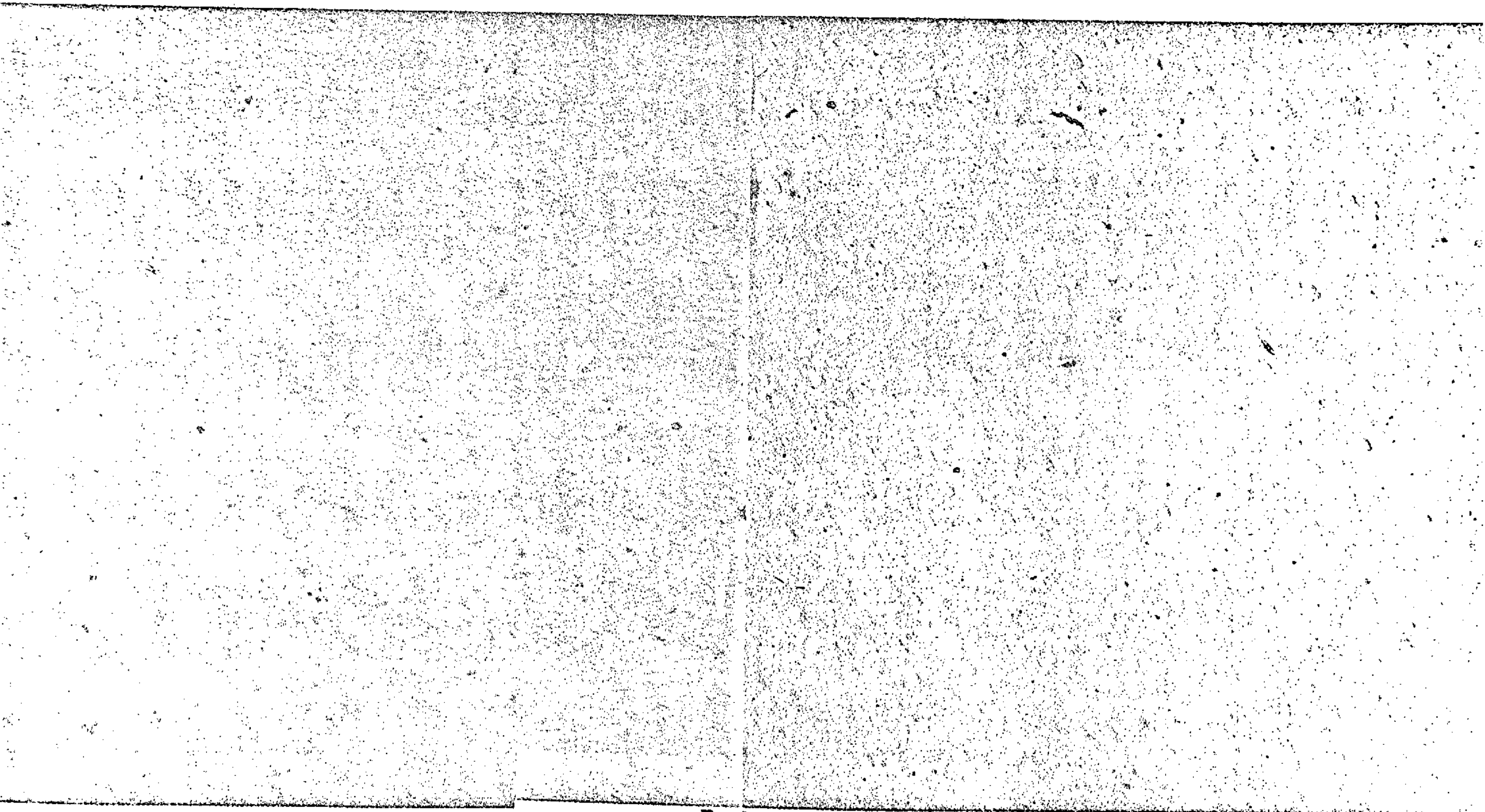
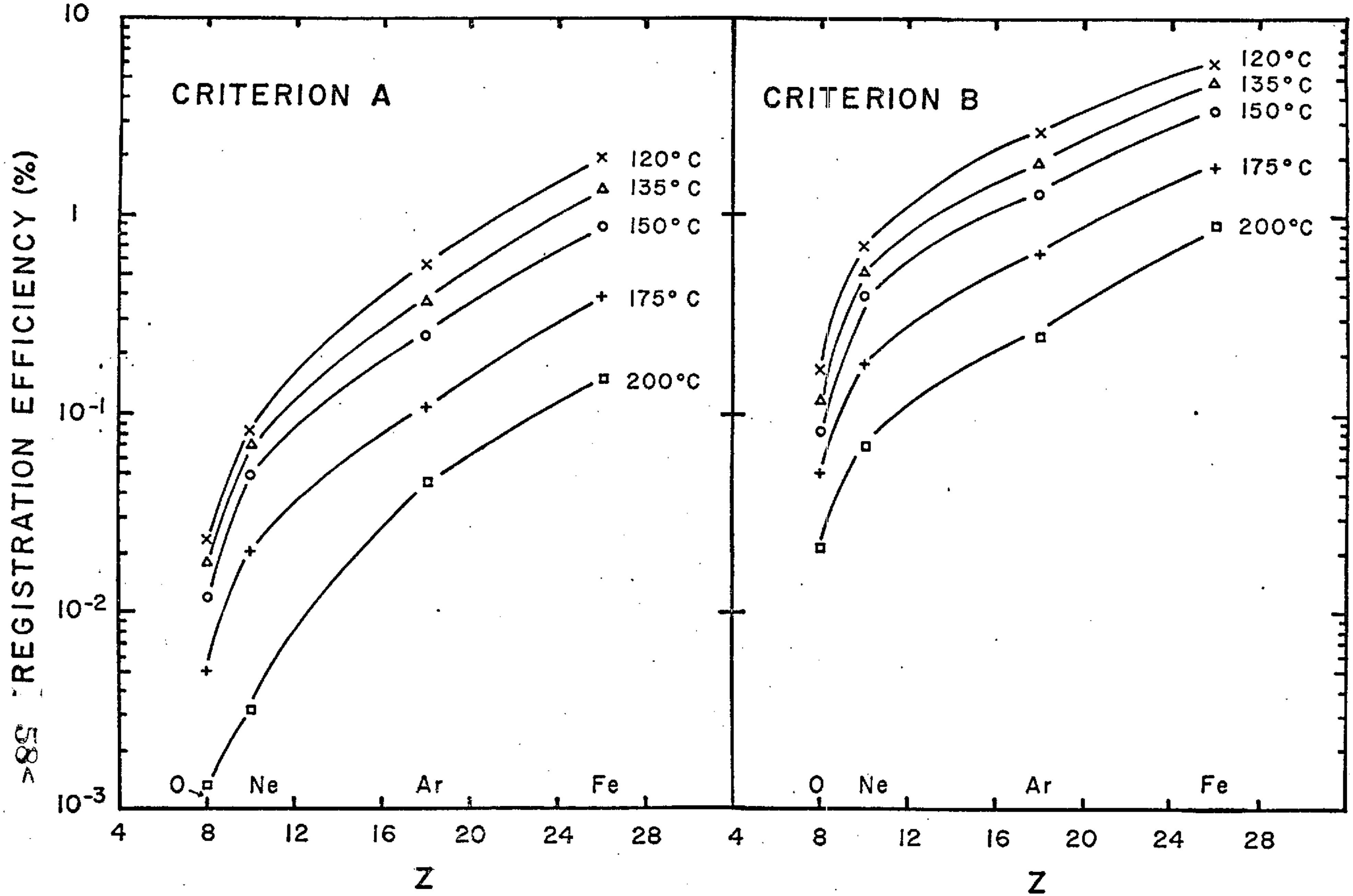


Fig 4

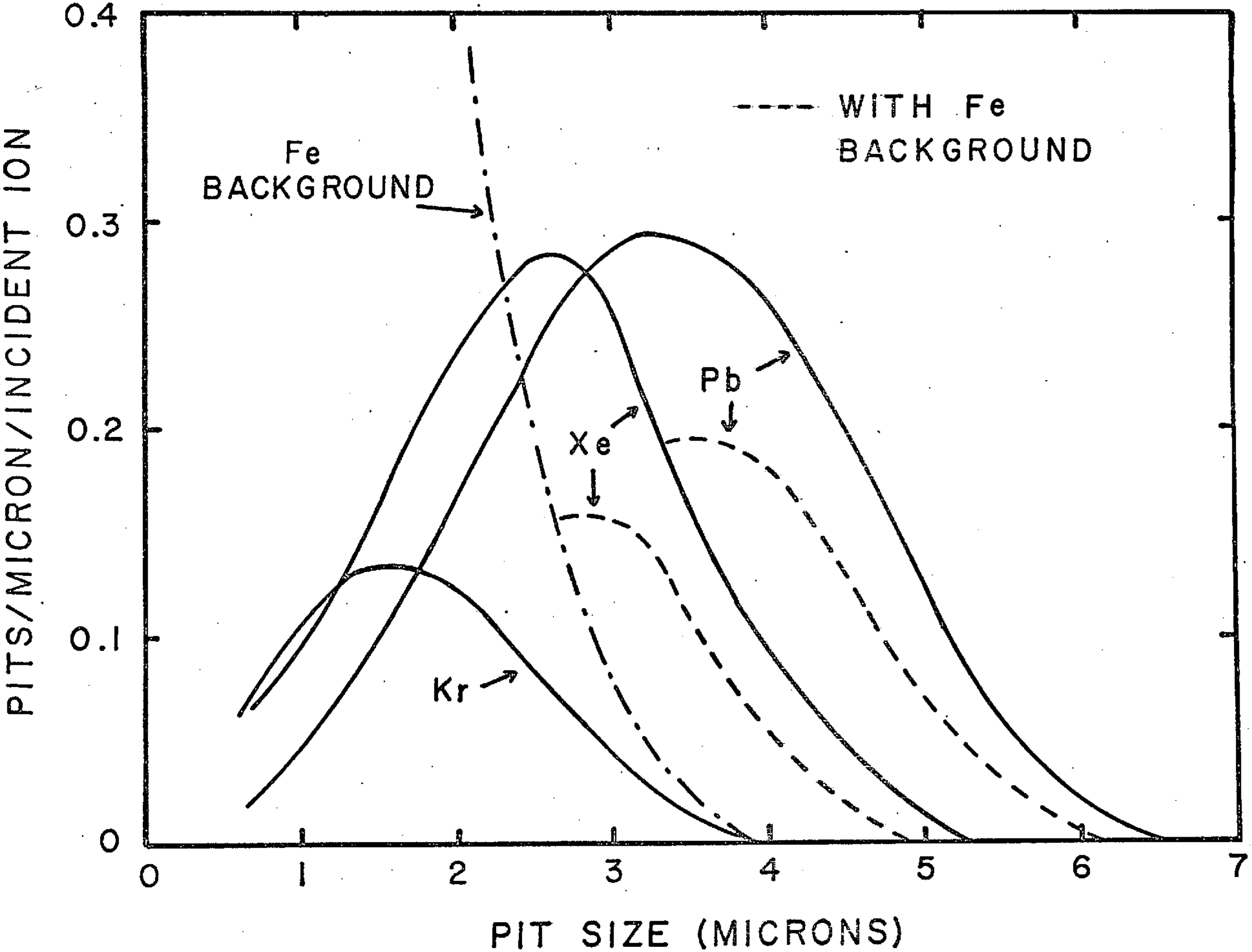


left Fig 5 right



CRITERION A
CRITERION B
REGISTRATION EFFICIENCY (%)
120° C
135° C
150° C
175° C
200°C
O
Ne
Ar
Fe
Z
10
1
10^{-1}
10^{-2}
10^{-3}
4
8
12
16
20
24
28

FIG. 6



0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
PITS/MICRON/INCIDENT ION
PIT SIZE (MICRONS)
WITH Fe BACKGROUND
Fe BACKGROUND
Pb
Xe
Kr

FIG. 7

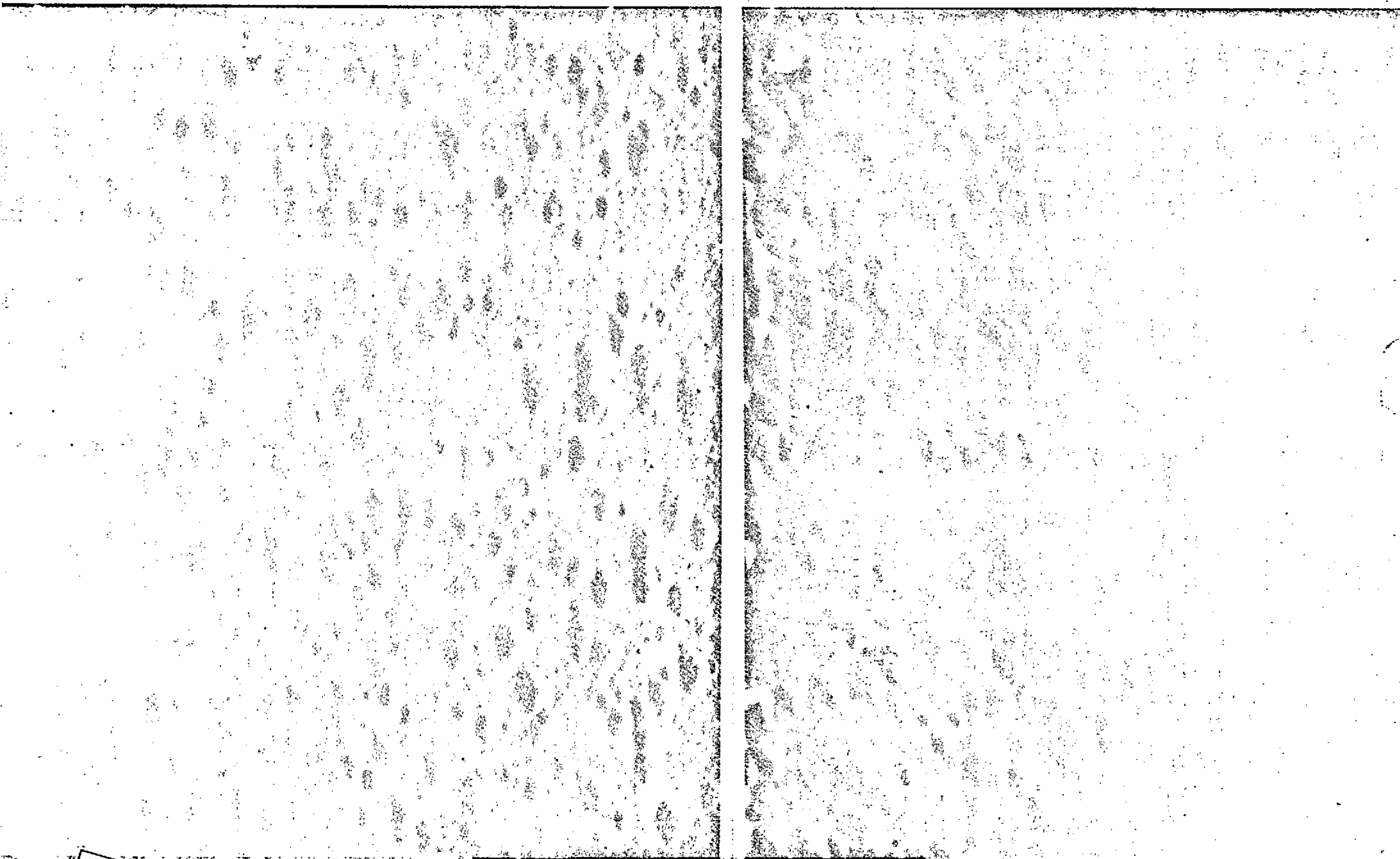


Fig 8 left — right

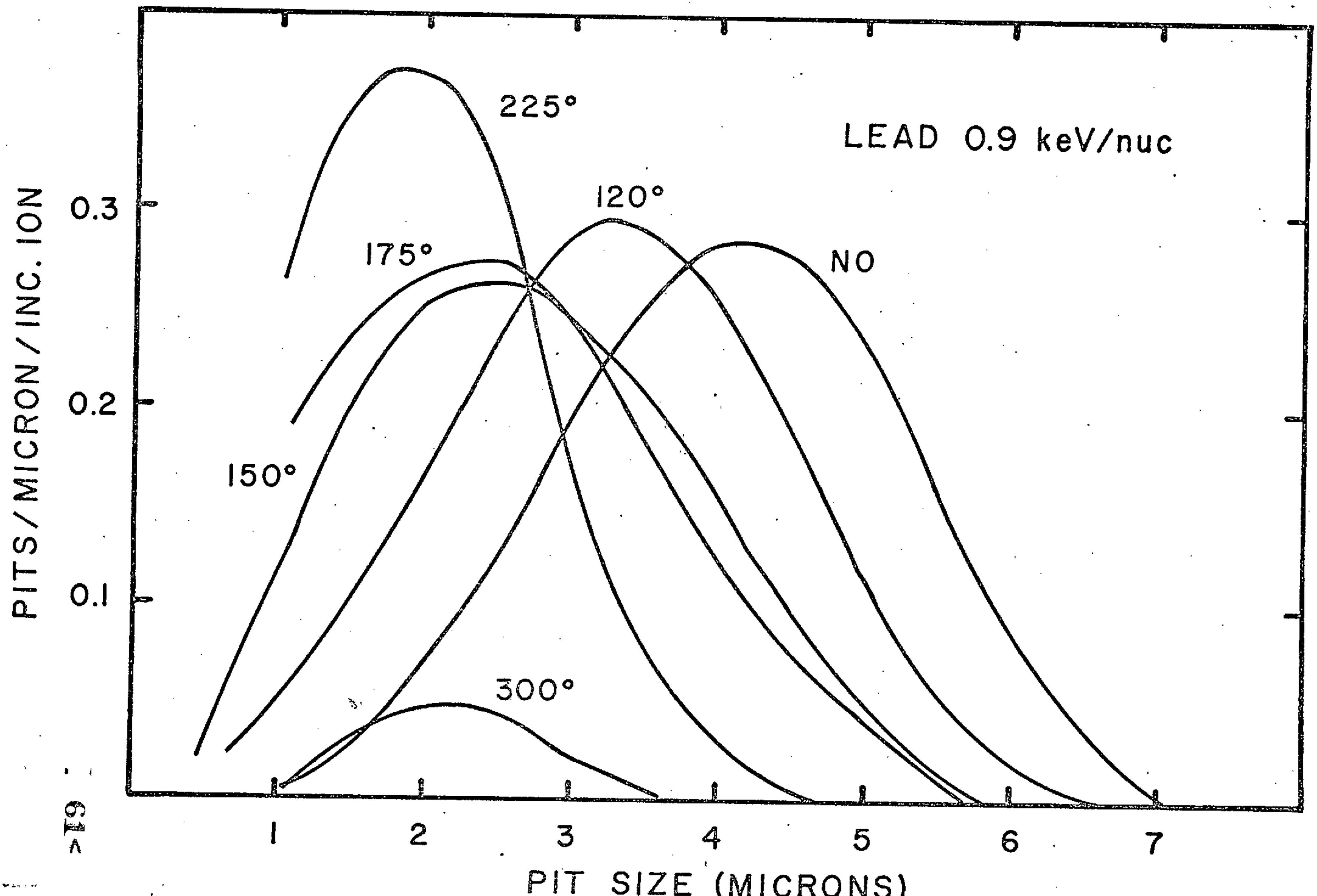

LEAD 0.9 keV/nuc
225°
120°
175°
NO
150°
300°
0.3
0.2
0.1
1
2
3
4
5
6
7
PITS / MICRON / INC. ION
PIT SIZE (MICRONS)

FIG. 9

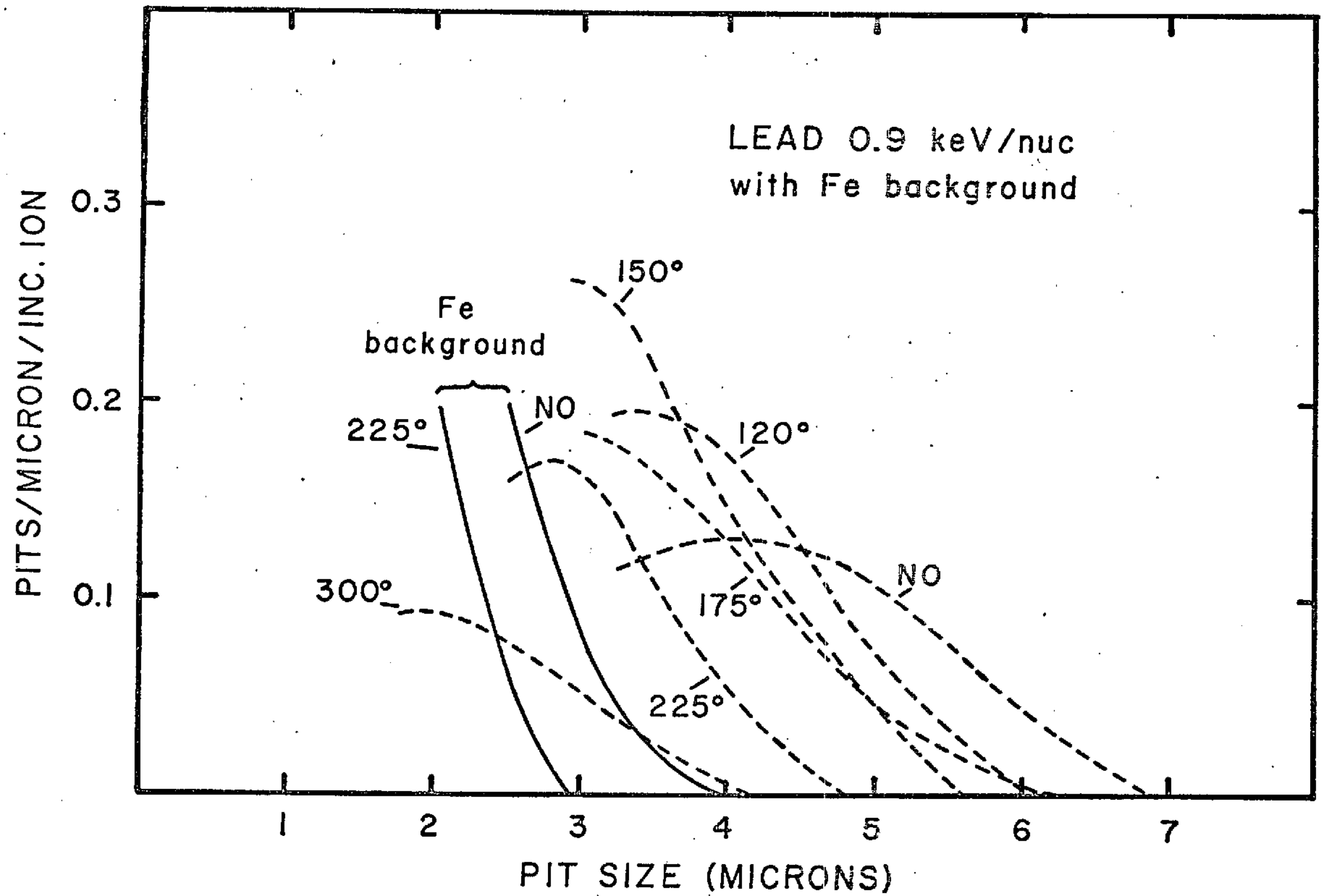

LEAD 0.9 keV/nuc
with Fe background
Fe
background
PITS/MICRON/INC. ION
PIT SIZE (MICRONS)
0.3
0.2
0.1
1
2
3
4
5
6
7
150°
120°
NO
225°
NO
175°
300°
225°

FIG. 10

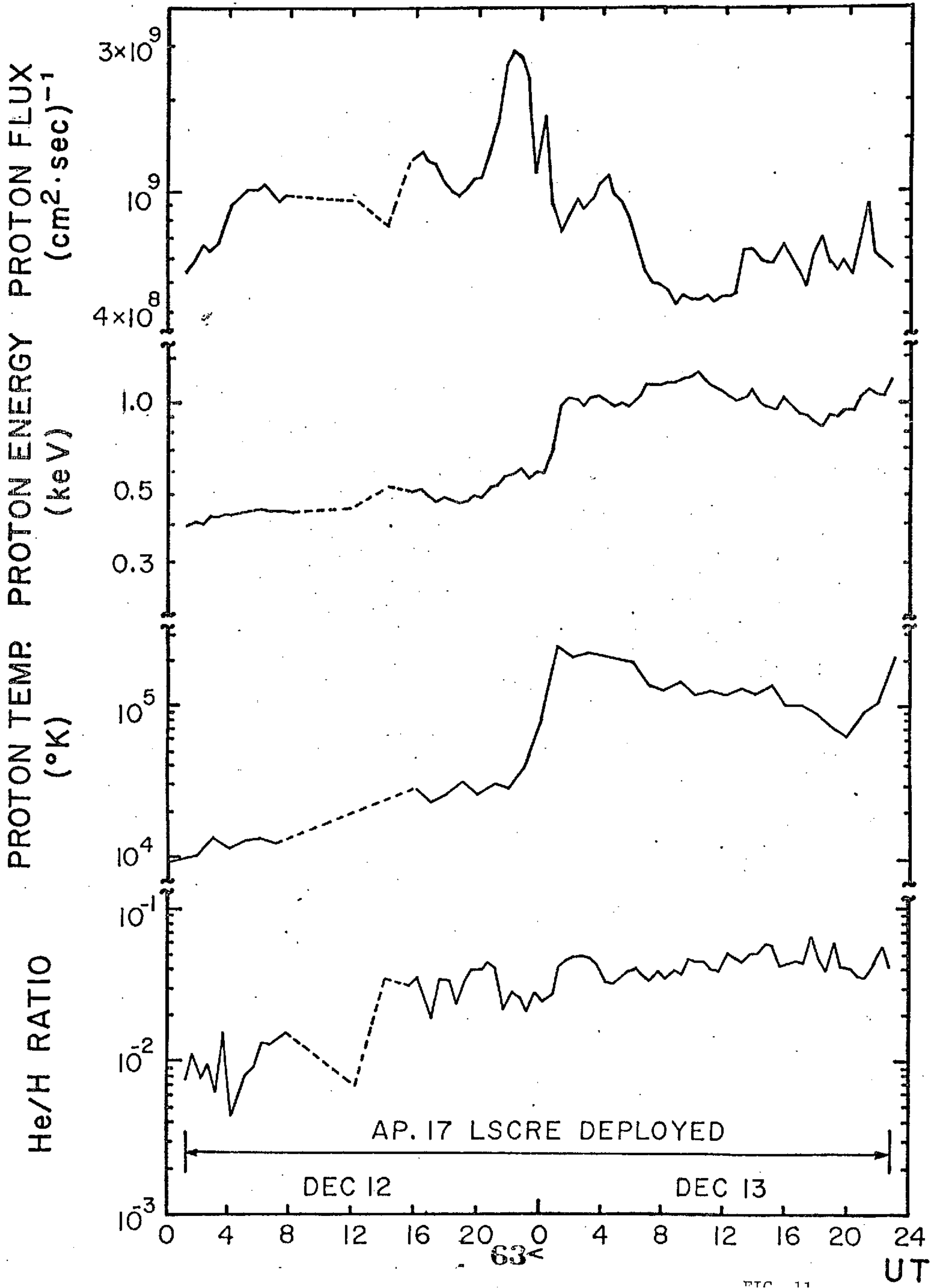
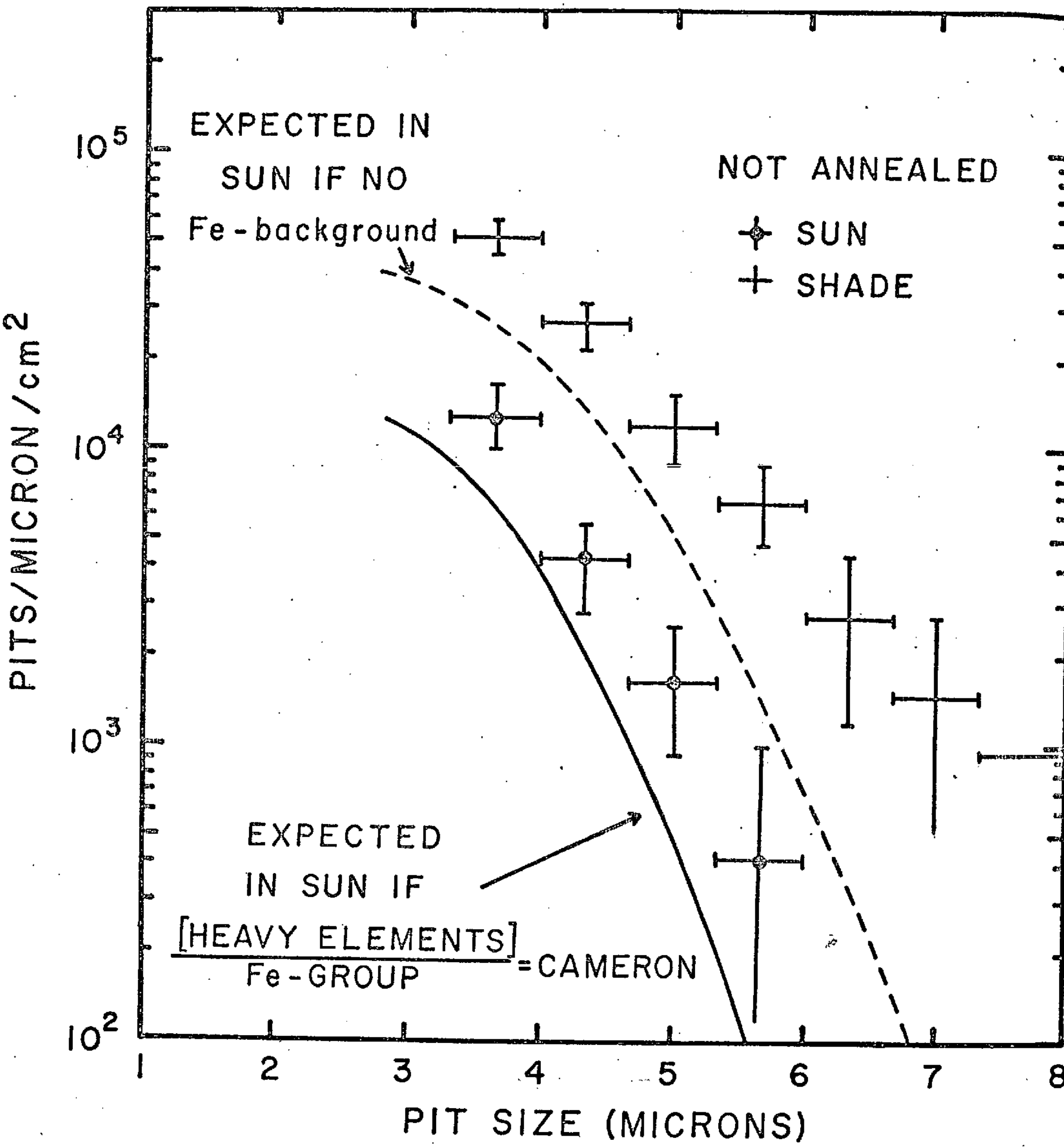
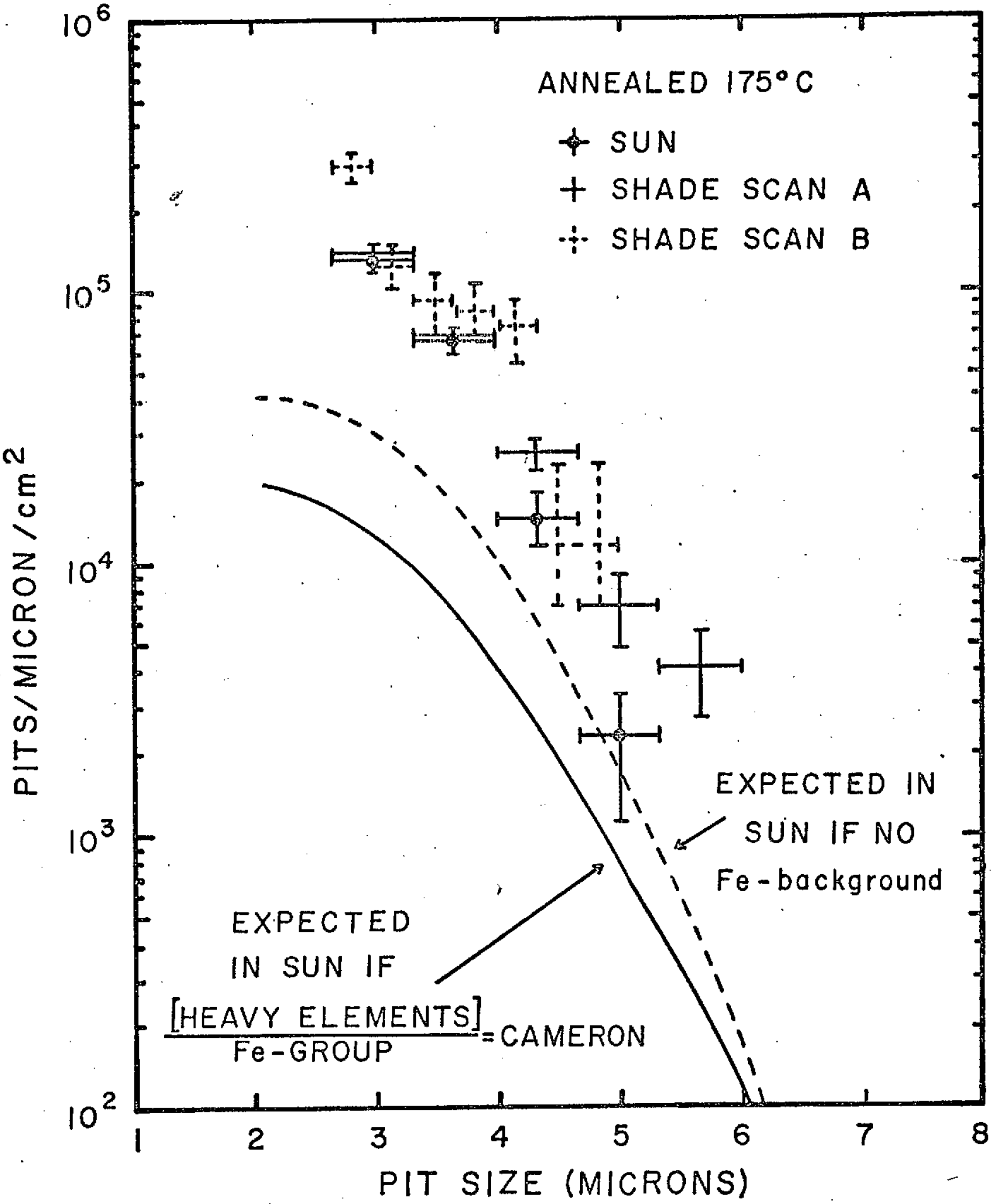

PROTON FLUX
$(cm^2 \cdot sec)^{-1}$
3×10^9
10^9
4×10^8
PROTON ENERGY
(keV)
1.0
0.5
0.3
PROTON TEMP.
(°K)
10^5
10^4
He/H RATIO
10^{-1}
10^{-2}
10^{-3}
AP. 17 LSCRE DEPLOYED
DEC 12
DEC 13
0 4 8 12 16 20 0 4 8 12 16 20 24
UT

FIG. 11



EXPECTED IN
SUN IF NO
Fe-background
NOT ANNEALED
SUN
SHADE
EXPECTED
IN SUN IF
[HEAVY ELEMENTS]
Fe-GROUP
=CAMERON
PITS/MICRON/cm²
PIT SIZE (MICRONS)

FIG. 12



ANNEALED 175°C
SUN
SHADE SCAN A
SHADE SCAN B
EXPECTED IN SUN IF NO Fe-background
EXPECTED IN SUN IF
[HEAVY ELEMENTS] / Fe-GROUP = CAMERON
PITS/MICRON/cm²
PIT SIZE (MICRONS)
10⁶
10⁵
10⁴
10³
10²
1
2
3
4
5
6
7
8

FIG. 13

(Submitted, Proc. Third Solar Wind Conf.)

Measurement of Heavy Solar Wind Particles During the Apollo 17 Mission

E. Zinner and R. M. Walker, Laboratory for Space Physics,
Washington University, St. Louis, Mo. 63130
and
J. Borg and M. Maurette, Laboratoire René Bernas,
Orsay, France

The Apollo 17 Lunar Surface Cosmic Ray Experiment (LSCRE) consisted of a series of metal foils and nuclear track detectors designed to measure light and heavy solar wind particles as well as more energetic solar and galactic nuclei (Fig. 1). One half of the experiment was mounted in the sun and the other half in the shade for a total of 45.5 hours on the moon. During this time the flux of protons of energies > 3 MeV did not exceed that of quiet sun conditions. However, proton and He fluxes in the range of 29 keV/nuc to 1.8 MeV/nuc as measured on IMP-6 (1), Vela 6A (2), IMP-7 (3) and Pioneer 10 (3) rose to levels more than a factor of 10 higher than typical quiet time counts during the second half of the period of deployment (Fig. 2). We report here fluxes of solar wind particles based on an analysis of the mica detectors. Results for more energetic particles have previously been reported by us and the G. E. and Berkeley groups (4-8). The abundances given by the Berkeley group for particles with energies from 0.2 to 40 MeV/nuc indicate a mixture of solar and galactic particles.

Calibration Experiments

Heavy ions of solar wind energy (∿1 keV/nuc) produce shallow pits in etched mica (9). We used two different etching times and two methods of observation to study particles in different mass ranges. Samples etched for 10 min in a 40% HF solution at 30°C were studied using Pt-C replicas and a transmission electron microscope. Samples etched for 2 hrs were silvered and studied with an optical microscope using interference contrast in reflected light (Nomarski method for Zeiss microscopes). The shorter etching was used for the abundant lighter elements (CNO to Fe), the second for less abundant heavier masses. Calibration irradiations were made with 0.9 keV/nuc ions of O, Ne, Ar, and Fe at fluxes between $5 \times 10^8/cm^2$ and $5 \times 10^{11}/cm^2$. Pit size distributions and registration efficiencies were measured as a function of temperature to account for annealing on the moon and to separate charge groups by differential annealing. Pit sizes for all ions range from zero to a maximum of 0.8 microns after a 10 min etch; neither the average width nor the size distribution exhibit a strong mass dependence. However, there is a marked mass dependence of the depth of pits; pits produced by Fe ions are deeper than those produced by O ions and the former can clearly be separated from the latter. Figure 3 shows the registration efficiencies of various ions after annealing at different temperatures applying two different depth criteria for the acceptance of pits. No difference in pit morphologies was found for Fe^+, Fe^{++}, and Fe^{+++} calibration ions. After 2 hrs etching, Kr, Xe, and Pb ions of 0.9 keV/nuc give pits that increase in average size with increasing mass (see Fig. 4). Calibration experiments show that the pit distributions for these heavier elements are modified and the registration efficiency decreased by the presence of large numbers of Fe and lighter ions. The lunar environment was simulated by studying the registration and annealing of heavy particles in samples that also contained 1.5×10^9 Fe ions/cm^2 (see Fig. 4). Annealing of an irradiated sample reduces both the average size and the number of pits produced by subsequent etching affecting lighter ions more than heavier ones (e.g., annealing at 175°C for 72 hours reduces the total registration efficiency for Kr by a factor of three while producing only a 10% reduction in the registration efficiency of Pb). Thus partial annealing provides a method for ameliorating the adverse effects of the large background of lighter ions: there is a flat maximum for the efficiency of detecting large pits at the presence of Fe background between 150°C and 200°C. Measurement of the registration of Mn, Kr, and Xe as a function of bombarding angle showed only small effects.

Abundance of Fe-Group Elements

The mica samples exposed in the sun had fifty times as many small pits as those exposed in the shade. By analyzing a sun mica piece as returned from the moon and one pre-annealed for 24 hrs at 200°C, we derive an Fe-group flux in the solar wind of $3.9 \pm 1.0 \times 10^4/\text{sec cm}^2$. To relate this value to the light rare gas fluxes, we still have to await the results of the analysis of the metal foils. As shown in Fig. 5, H and He solar wind fluxes were measured during this period on IMP-7 (10). The average solar wind proton flux for the period of LSCRE deployment is $8.9 \times 10^8/\text{cm}^2\text{sec}$. Combining our Fe-flux with this value gives an Fe/H ratio of 4.1×10^{-5}. This compares with 3.4×10^{-5} (11) and 5.4×10^{-5} (12) of Vela satellite data of the Los Alamos group and with Cameron's solar system abundance (13) of 2.6×10^{-5}. Because of the extreme shallowness of oxygen pits and the large errors on the registration efficiencies, only a crude upper limit estimate can be made on the

CNO abundance. We obtain a flux of 2.4×10^6/sec cm^2 and a corresponding CNO/H ratio of 2.7×10^{-3} which is 2.5 times the solar system value.

Experimental Results on Large Pits

We previously reported a puzzling lack of large pits (4). We now understand that this is due to a combination of the suppression of large pits by the background of small ones and annealing effects on the moon. Our conclusions on the abundance of extremely heavy ions is limited by a background of pits produced by the more energetic particles that were present in the interplanetary medium during the mission (4-8). Calibration irradiations with Na, Ar, and Fe ions with energies up to 30 keV/nuc have shown that pits from such particles are very shallow and cannot in many cases be distinguished from solar wind pits. Fig. 6 shows the results of the analysis of sun and shade micas without any pre-annealing. The background observed in the shade mica sets an upper limit on the heavy element abundances in the solar wind. We can rule out an overabundance of $Z > 45$ elements relative to Fe by more than a factor of ~ 4.

References

1) R. P. Lin, private communication.

2) I. D. Palmer, private communication.

3) J. A. Simpson, private communication.

4) Report 19, Cosmic Ray Experiment, by R. M. Walker et al, P. B. Price et al, and R. T. Woods et al, in the Apollo 17 Preliminary Science Report, NASA, 1973.

5) R. T. Woods et al, 13th Intl. Cosmic Ray Conference, Conference Papers, Vol. 2, 1644, Denver, 1973.

6) P. B. Price et al, ibid, Vol. 1, 146.

7) J. H. Chan et al, ibid, Vol. 2, 1650.

8) P. B. Price et al, ibid, Vol. 2, 1479.

9) W. H. Huang and R. M. Walker, Science 155, 1103, 1967.

10) W. C. Feldman, private communication.

11) S. J. Bame et al, J. Geophys. Res. 75, 6360, 1970.

12) S. J. Bame et al, Abstract SS22, Transactions, Amer. Geophys. Union 55, 410, 1974.

13) A. G. W. Cameron, Space Science Rev. 15, 121, 1973.

Figure Captions

Fig. 1 — Detectors of the Lunar Surface Cosmic Ray Experiment. #1 sun mica (heavy solar wind), #2 and #3 metal foils (#2 light solar wind, #3 for control), #4 glass detectors and #5 Lexan stack (more energetic particles), #6 shade mica.

Fig. 2 — High energy proton and alpha particle counting rates from three satellite detectors on IMP-6 (R. P. Lin, private communication), Vela 6A (I. D. Palmer, private communication), and IMP-7 (J. A. Simpson, private communication) during Dec. 12 and 13 (Universal Time), the period of LSCRE deployment. All three spacecrafts have geocentric orbits.

Fig. 3 — Registration efficiencies of various ions of 0.9 keV/nuc after annealing at various temperatures and etching for 10 min in 40% HF at 30°C. In addition to 24 hrs at the indicated higher temperatures, all samples have been annealed for 45.5 hrs at 120°C (the temperature the LSCRE reached on the moon) prior to etching. Two different criteria have been applied for the acceptance of pits. Criterion A represents counting pits greater than a certain depth; with criterion B pits surpassing a minimum width are counted independent of depth.

Fig. 4 Pit size distribution for 0.9 keV/nuc Kr, Xe, and Pb ions after annealing at 120°C for 45.5 hrs followed by 2 hrs etching in 40% HF at 30°C. The areas under the curves give the total registration efficiencies. Also shown are the pit sizes for Xe and Pb in the presence of an Fe background of 1.5×10^9 ions/cm^2.

Fig. 5 Proton and He solar wind data from IMP-7 (W. C. Feldman, private communication) for the period of LSCRE deployment.

Fig. 6 Pit size distribution of large pits in sun and shade after 2 hrs etching. Plotted are pit sizes larger than those of the Fe-group background. The solid line indicates the pit size distribution expected from heavy solar wind particles based on our Fe-group dose and assuming solar system abundances (13). The dashed line does not take into account the reduction in registration efficiency by the Fe-group background.

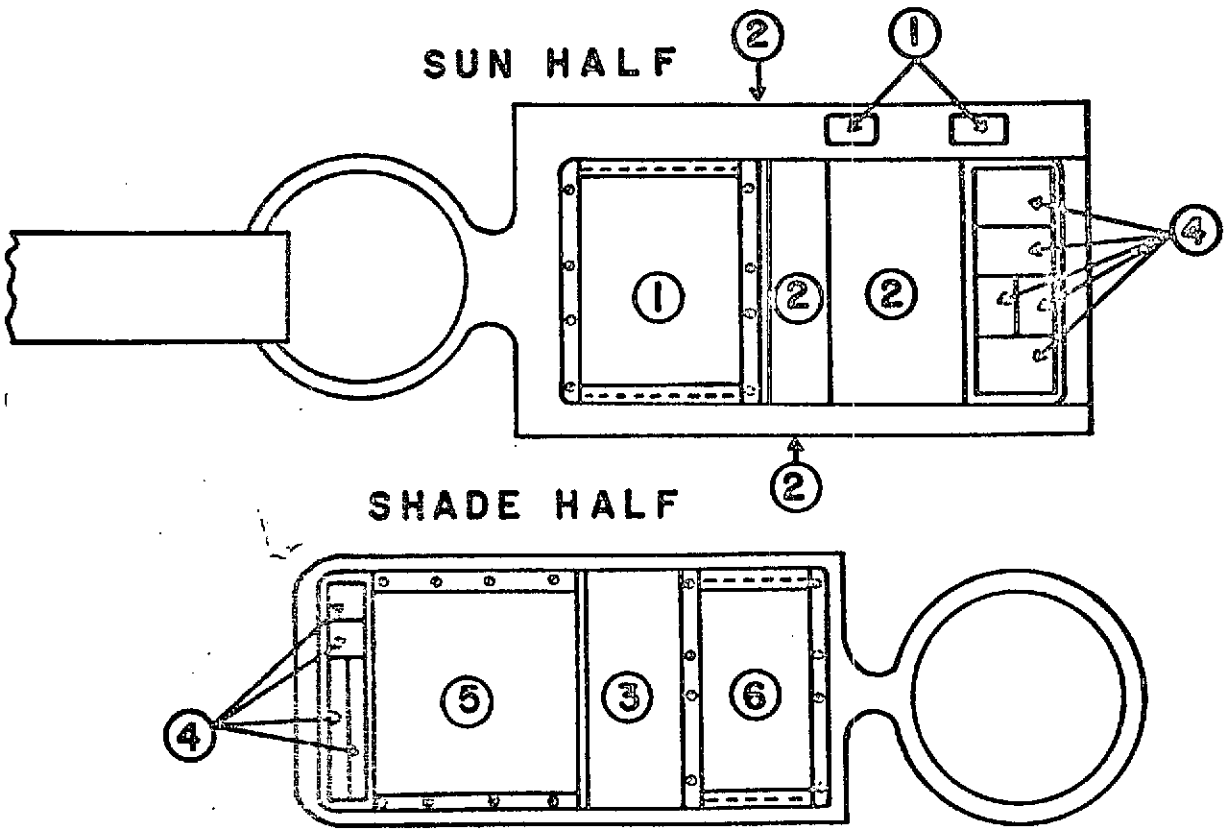
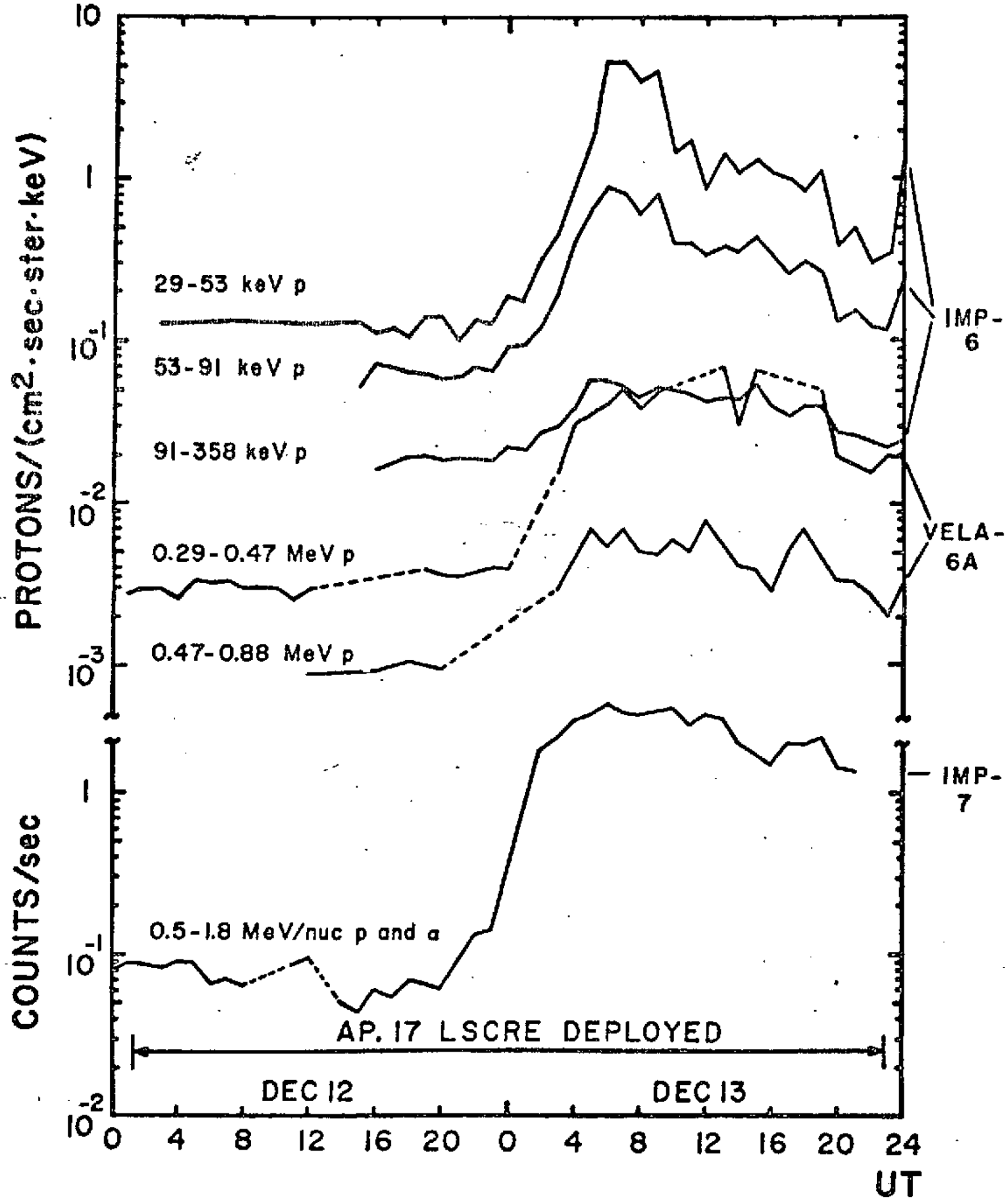
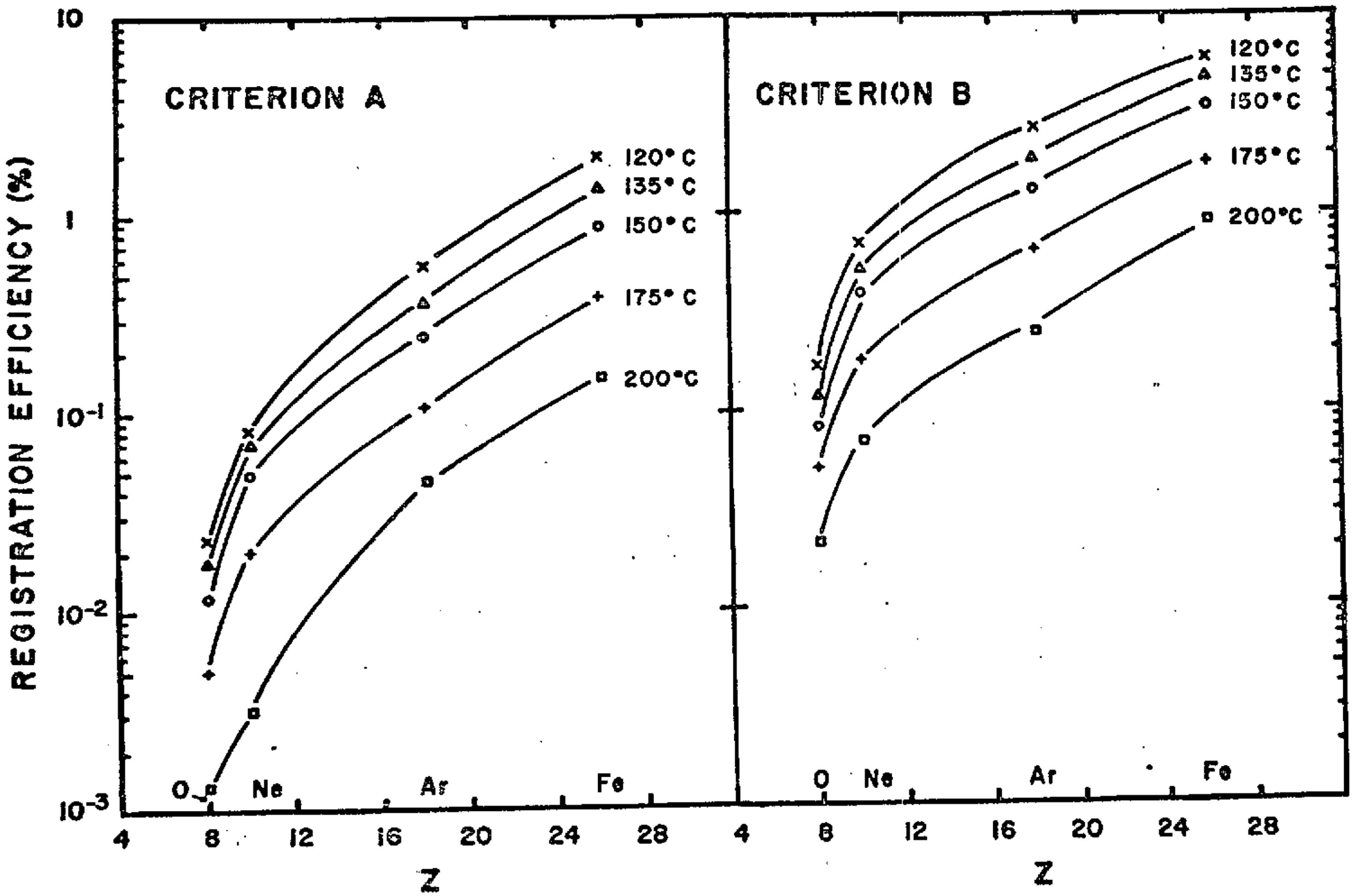


FIG. 1



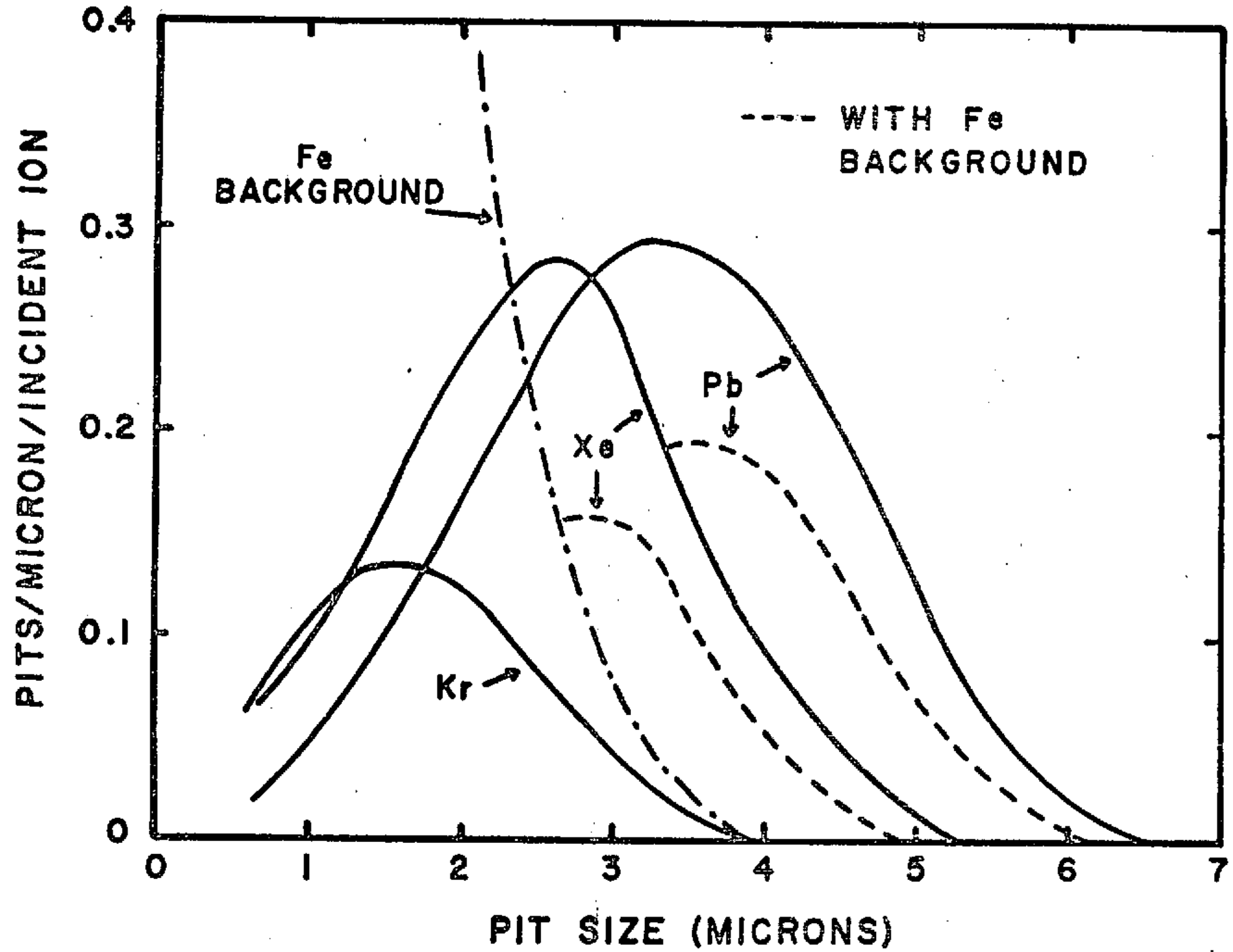
PROTONS/(cm2·sec·ster·keV)
COUNTS/sec
29-53 keV p
53-91 keV p
91-358 keV p
0.29-0.47 MeV p
0.47-0.88 MeV p
0.5-1.8 MeV/nuc p and α
IMP-6
VELA-6A
IMP-7
AP. 17 LSCRE DEPLOYED
DEC 12
DEC 13
UT

FIG. 2



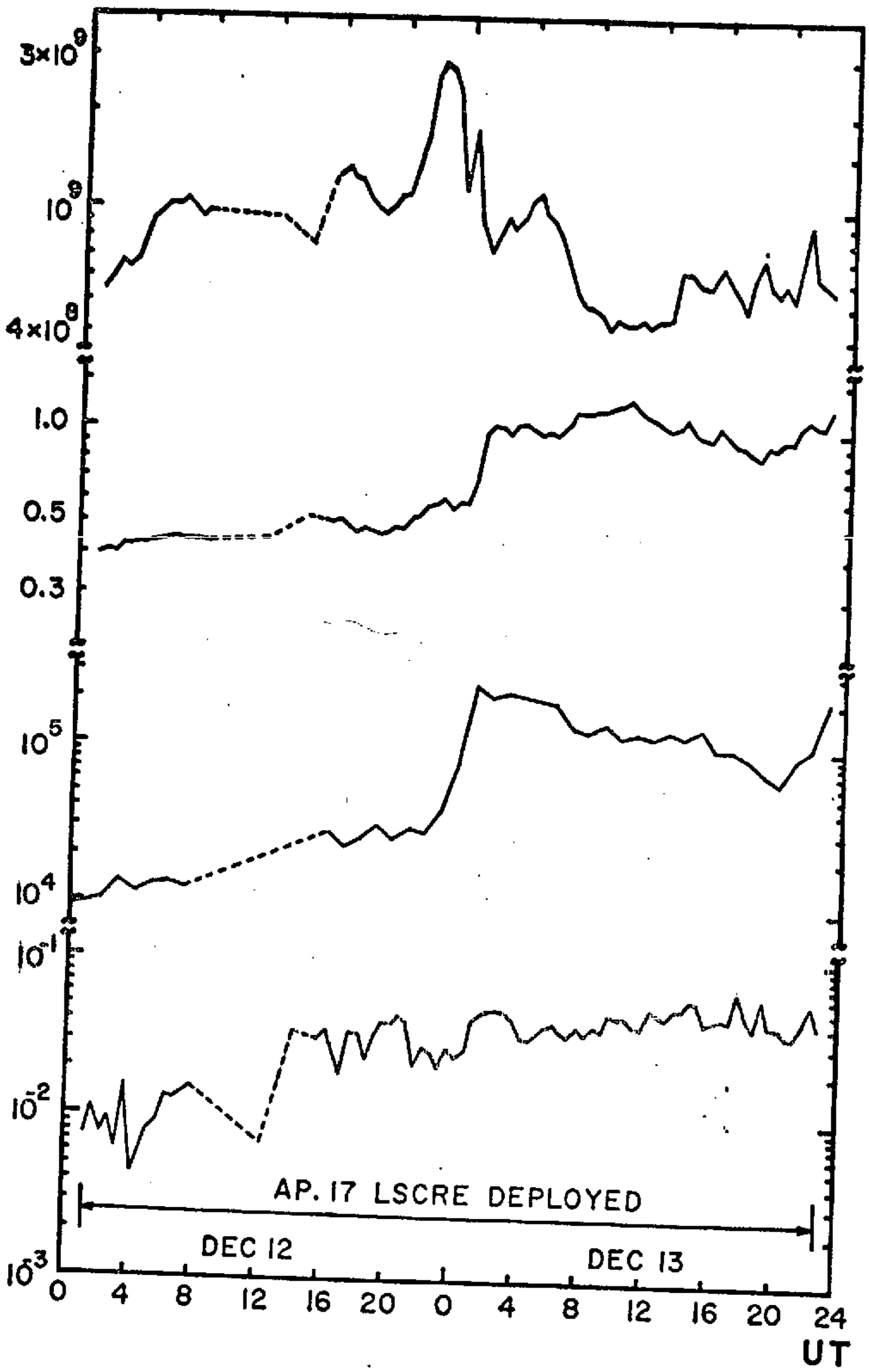
CRITERION A
CRITERION B
REGISTRATION EFFICIENCY (%)
120° C
135° C
150° C
175° C
200°C
O
Ne
Ar
Fe
Z

FIG. 3



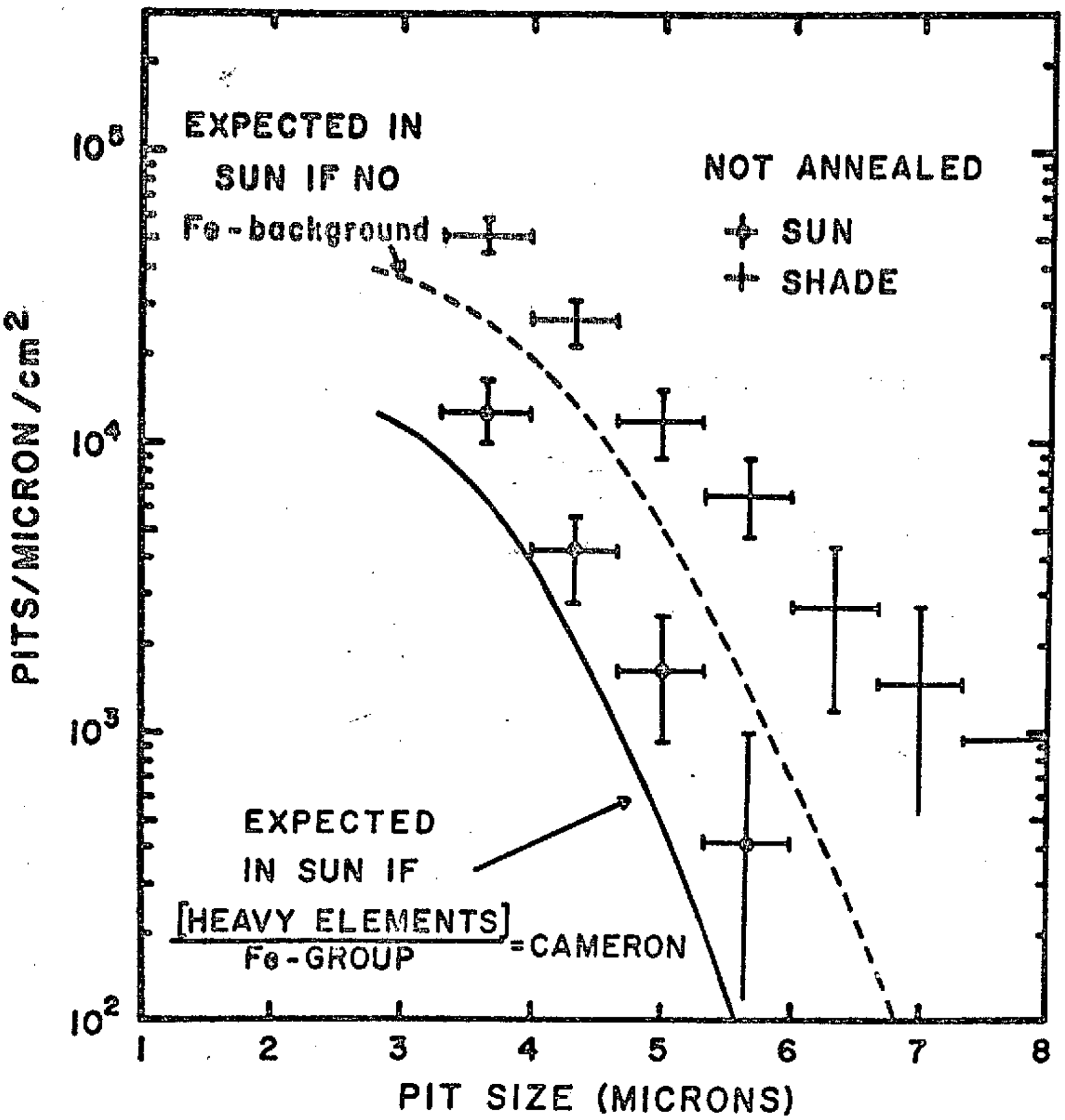
0.4
0.3
0.2
0.1
0
PITS/MICRON/INCIDENT ION
Fe
BACKGROUND
WITH Fe
BACKGROUND
Pb
Xe
Kr
0
1
2
3
4
5
6
7
PIT SIZE (MICRONS)

FIG. 4



PROTON FLUX (cm²·sec)⁻¹
3×10⁹
10⁹
4×10⁸
PROTON ENERGY (keV)
1.0
0.5
0.3
PROTON TEMP. (°K)
10⁵
10⁴
He/H RATIO
10⁻¹
10⁻²
10⁻³
AP. 17 LSCRE DEPLOYED
DEC 12
DEC 13
0
4
8
12
16
20
0
4
8
12
16
20
24
UT

FIG. 5



EXPECTED IN
SUN IF NO
Fe-background
NOT ANNEALED
SUN
SHADE
EXPECTED
IN SUN IF
[HEAVY ELEMENTS] / Fe-GROUP = CAMERON
PITS/MICRON/cm²
10⁵
10⁴
10³
10²
1
2
3
4
5
6
7
8
PIT SIZE (MICRONS)

FIG. 6

13th International Cosmic Ray Conf., Conference Papers, Vol. 2, Univ. of Denver, 1973.

CHARGE COMPOSITION AND ENERGY SPECTRUM OF SUPRATHERMAL SOLAR PARTICLES

J.H. Chan, P.B. Price and E.K. Shirk
Department of Physics, University of California
Berkeley, California 94720

During the Apollo 12 mission (14 to 24 Nov 1969) when the counting rate of 1 to 2 MeV/nucleon He was occasionally up to ~10^2 times higher than the quiet rate, we found the Fe/He ratio to be ~0.01 in the interval 0.5 to 5 MeV/nucleon, or enhanced by ~30±10 times over the photospheric Fe/He ratio. During the Apollo 17 mission a small Lexan stack was exposed on the moon from 11 to 13 Dec 1972. On 12 Dec the counting rate of 1 MeV/nucleon He went up by ~10X. From ~0.5 to ~10 MeV/nucleon we measured an abundance ratio He:CNO:[Z>20]=500:25:1 and spectra $\propto E^{-3}$. The O/(C+N) ratio is ≥1.6, which implies a solar origin. At energies below 0.5 MeV/nucleon the abundances of heavy elements appear to be increasing with decreasing energy.

1. Introduction. On two of the Apollo lunar missions (12 and 17) the sun was quiet except for one- to two-day periods in which the counting rates of protons and alpha-particles at very low energies (~1 to 2 MeV/nucleon) increased by ~10 to 100X over quiet-time levels. We have studied the composition and energy spectra of the particles emitted during these periods of weak solar activity to see if the heavy-element enhancements we have observed in major solar flares also occur during times of weak solar activity. In several strong flares the enhancement ratio, defined as $Q(Z,E)\equiv[Z/He]_{SP}/[Z/He]_{\odot}$, has been found to decrease with energy and to increase with Z at a given energy. From our studies of four flares on 25 Jan 1971, 2 Sept 1971, 17 Apr 1972 and 4 Aug 1972, it appeared that the heavy-particle enhancements persisted to higher energy the stronger the flare (Price et al, 1973a). The energy below which an enrichment of heavy elements could be detected was found to range from ~1 to ~15 MeV/nucleon in those four flares. One thus requires a detector capable of identifying particles of very low energy. In this work we have been able to identify particles down to ~0.2 MeV/nucleon, using a SiO_2 window from the Apollo 12 command module and a stack of Lexan plastic sheets mounted outside the Apollo 17 lunar module.

2. Spectra of Fe and He during Apollo 12. During the time of the Apollo 12 mission, 14 to 24 Nov 1969, the sun was quiet until 22 Nov, when the counting rate for He between ~1 and 2 MeV/nucleon increased by a factor ~200 for the last two days of the mission, as measured by Lanzerotti's detector on IMP-G. The He spectrum from 1 to 10 MeV/nucleon, summed over the eleven-day period and expressed as an average flux, is plotted in Fig. 1. It should be noted that IMP-G was in the earth's magnetotail during the entire Apollo 12 mission, and we are assuming complete access of solar particles to the magnetosphere when we compare He data from IMP-G with our data from the Apollo 12 spacecraft in transit to and from the moon.

A portion of the right rendezvous window from the Apollo 12 command module was etched for various times in 5% HF at 23°C. Cellulose acetate replicas of the surface were made after each etch time and shadowed at 70° to the vertical

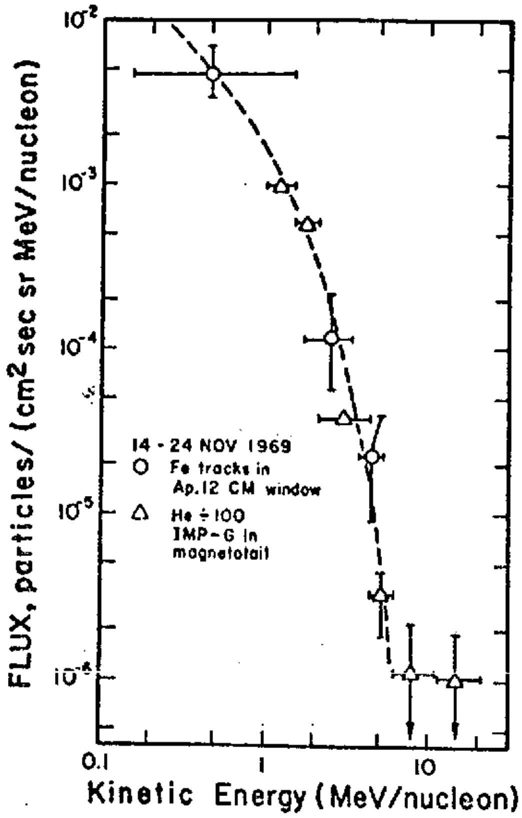


Fig. 1. Average flux of Fe and He nuclei during the eleven-day Apollo 12 mission. He data are from Lanzerotti's detector on IMP-G.

with Sn to facilitate scanning and measuring. This technique is necessary both because the glass is too thick to be studied microscopically and because the etch pits have a large cone angle and are easier to measure on the replica than in the glass. A prior calibration of SiO_2 glass with a beam of ^{56}Fe ions established that over 80% of the pits we saw in the window were produced by Fe ions. The energy spectrum of the Fe nuclei is plotted in Fig. 2.

Within the indicated errors the spectra of He and Fe have similar shapes. Though a power law is not a particularly good representation, we can represent their spectra approximately by E^{-4}. The He flux is only ~100 times higher than the Fe flux, in contrast to the solar abundance ratio, which, though still somewhat poorly known, is probably ~3000±1000. Thus, during the interval 14 to 24 Nov 1969 the Fe/He ratio for energetic particles was 30±10 times higher than for the photosphere, in the energy interval ~1 to ~5 MeV/nucleon.

3. Composition and spectra of interplanetary particles during Apollo 17. The Apollo 17 astronauts deployed a Lexan stack on the side of the lunar module facing away from the sun for 45.5 hours beginning 0123 UT, 12 Dec 1972. The stack consisted of 7 sheets each 125μ x 3.5 cm x 4.5 cm. The top sheet was coated with an ~1000Å layer of Al to screen out ultraviolet light. Small portions of sheets 1 and 3 were bombarded with ^{16}O ions prior to the flight. These tracks were useful in confirming that we were identifying ^{16}O ions correctly. Various portions of the stack were processed in different ways optimized for different charge intervals. Here we report data only for He, C, O, CNO, and Z≥20, at energies from ~0.2 to ~20 MeV/nucleon. Figure 2 displays our spectra for Apollo 17 together with data for galactic CNO and Z≥20 at energies above 40 MeV/nucleon obtained on the Apollo 16 mission (Price et al, 1973b). At

energies below ~0.3 MeV/nucleon Woods et al (1973) have studied particles with Z≥20 using glass detectors mounted adjacent to the Lexan stack. Their data, shown in Fig. 2 as solid triangles, are quite consistent with our data for Z≥20 in the region of overlap. In the interval ~0.5 to ~10 MeV/nucleon the spectra of all the elements are $\sim\propto E^{-3}$.

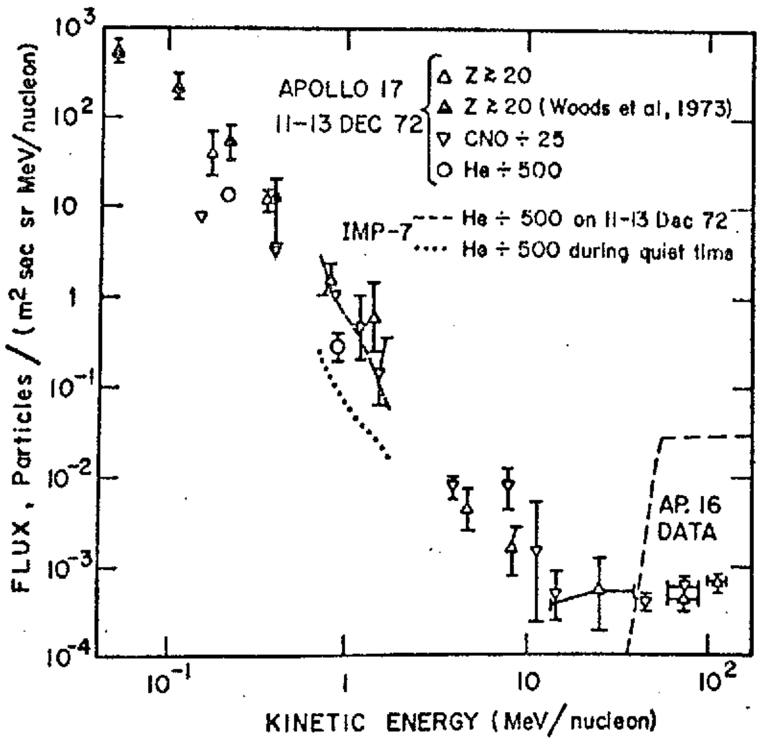


Fig. 2. Average flux of Fe, CNO, and He during 45 hours when Apollo 17 astronauts were on the moon. Also shown are quiet-time He from Chicago detector on IMP-7 and galactic CNO and nuclei with 23≤Z≤28 from Apollo 16 experiment (Price et al, 1973b).

He data from the University of Chicago detector on IMP-7 are plotted in Fig. 2 for the time of our Apollo 17 exposure as well as for quiet-time on 5 Oct 1972. The increase by ~ an order of magnitude in the counting rate for He of 1 to 2 MeV/nucleon over the quiet-time level suggests, but does not prove, that most of the particles of low energy that entered our detector originated in the sun.

As an additional diagnostic test of the origin of the low-energy particles, we have determined the abundance ratio [O]/[C+N] at a mean energy of 3.9 MeV/nuc. The result is shown in Table 1, along with our measurements of the He:CNO:Fe ratios.

Table 1. Composition of Particles in Space

	Sun	Solar Flare Particles	Galactic Cosmic Rays	Particles on 11-13 Dec 1972	
				0.5 to 1 MeV/N	3.4 to 4.4 MeV/N
O:[C+N]	1.67	~1.65	0.74		≥1.6
He:CNO:[Z>20]	~3000:50:1	~800:30:1 to ~3000:60:1	~200:13:1	~500:25:1	~500:25:1

4. Discussion.

a) Origin of interplanetary particles with E≲10 MeV/nucleon. We know that the solar wind continuously populates interplanetary space with particles of energy very close to 1 keV/nucleon. Observations of tracks in lunar grains a few microns in size, using high-voltage electron microscopy (Borg et al, 1970; Barber et al, 1971), have established that over a long period of time the sun is a copious source of heavy particles with energies below ~1 MeV/nucleon but above solar wind energies. Studies of tracks in the glass filter from the Surveyor III camera showed that over a 2.6 year period the time-averaged spectrum of interplanetary heavy ions monotonically decreases with energy (roughly as E^{-3}) beginning at energies at least as low as ~0.5 MeV/nucleon (Crozaz and Walker, 1971; Fleischer et al, 1971; Price et al, 1971). Both the lunar grains and the Surveyor glass were populated overwhelmingly with tracks from solar flare particles and do not tell us about the energetic particle content of interplanetary space in the time intervals between flares. Using the presence of ^{2}H ions as a tracer of particles of galactic origin, Hsieh and Simpson (1969) showed that solar protons accounted for less than 15% of the interplanetary proton flux at ~20 MeV during quiet times in 1967. More recently, several instruments capable of identifying nuclei with energies ≲1 MeV/nucleon have begun operating on satellites, but with such small collecting power that it is difficult to study particles with Z>2 during quiet times.

With plastic detectors it is perfectly feasible to identify particles with Z≳2 at energies down to ~0.2 MeV/nucleon during quiet times, but unfortunately the sun rarely seems to be completely quiet! The Apollo 17 experiment represents our closest approach to solar quiet conditions. At 1 MeV/nucleon the flux of Fe nuclei was four orders of magnitude below the average value during the 2.6 year interval sampled by the Surveyor glass. Still, from the tenfold increase in the He spectrum observed by Simpson (1973), we must suspect that some fraction, perhaps the vast majority, of the particles with energies below ~10 MeV/nucleon originated in a small flare on 12 Dec 1972. Our measurements of the O/(C+N) ratio summarized in Table 1 strongly support the conclusion that the majority of particles in the CNO group at energies from ~0.5 to at least 4.4 MeV/nucleon were solar rather than galactic. Our measurements of the ratio He:CNO:[Z>20] are less conclusive. The results appear to be closer to the values ~800:30:1 observed by Bertsch et al (1973) and by Price et al (1973a) for particles in the flares on 25 Jan 1971 and 2 Sept 1971 than to the values for galactic cosmic rays. In paper 363, Price et al (1973b) have shown that the nuclei with Z≥17 are of galactic origin at all energies above about 10 MeV/nucleon. The nature of the quiet-time flux at energies below ~10 MeV/nucleon is still not settled. Plastics have the necessary collecting power and resolution but need to be deployed and recovered at just the right time.

b) Energy-dependent composition of solar particles. The first evidence for an enrichment of heavy nuclei in solar flares (Price et al, 1971) came from a comparison of Fe tracks in the Surveyor glass with the He flux measured in Lanzerotti's detector on IMP-G. The ratio of [Z>20]/He inferred in this way was ~100 to 200 and approximately independent of energy. In our Apollo 12 experiment described in section 2, we have followed a similar procedure and found that the ratio of [Z>20]/He was ~100, also independent of energy. Because the He and the nuclei with Z>20 were measured with separate detectors in different regions of interplanetary space, we cannot be as confident of the correctness of the results for the Surveyor glass and the Apollo 12 mission as when all nuclei from He to Fe are measured in the same detector. The observations of energy-dependent composition reported in paper 365 (Price et al, 1973a) are internally consistent, as are the results in Fig. 2 for Apollo 17. At the lowest energies in Fig. 2, below ~0.5 MeV/nucleon, there is an indication that the heavy elements become increasingly abundant with decreasing energy. The measurements are still in progress, and final results will be presented at the time of the Conference.

Acknowledgments. We are indebted to Richard Baldwin of the Johnson Space Center for arranging for the loan of the Apollo 12 window, to R. M. Walker and Ernst Zinner for the success of the Apollo 17 experiment, to J. King and E.R. Hoppe of the National Space Science Data Center for the He data during Apollo 12, to J. A. Simpson for the He data during Apollo 17, to Joan Steel for experimental assistance, and to Mary Klash for manuscript preparation.

References

Barber, D.J., Hutcheon, I., and Price, P.B. 1971, Science 171, 372.

Bertsch, D.L., Biswas, S., Fichtel, C.E., Pellerin, C.J., and Reames, D.V. 1973, Solar Physics, in press.

Borg, J., Dran, J.C., Durrieu, L., Jouret, C., and Maurette, M. 1970, Earth Planet. Sci. Lett. 8, 379.

Crozaz, G., and Walker, R.M. 1971, Science 171, 1237.

Fleischer, R.L., Hart, H.R. Jr., and Comstock, G.M. 1971, Science 171, 1240.

Hsieh, K.C., and Simpson, J.A. 1969, Ap. J. (Letters) 158, L37.

Price, P.B., Hutcheon, I.D., Cowsik, R., and Barber, D.J. 1971, Phys. Rev. Lett. 26, 916.

Price, P.B., Chan, J.H., Crawford, H.J., and Sullivan, J.D. 1973a, These Proceedings, paper 365.

Price, P.B., Chan, J.H., O'Sullivan, D., and Thompson, A. 1973b, These Proceedings, paper 363.

Simpson, J.A. 1973, private communication.

Woods, R.T., Hart, H.R. Jr., and Fleischer, R.L. 1973, Apollo 17 Preliminary Science Report, NASA Special Publication, in press.

Anomalies in the Composition of Interplanetary Heavy Ions with 0.01<E<40 MeV/amu

J. H. Chan and P. B. Price

Department of Physics, University of California, Berkeley 94720

Abstract

Analysis of tracks in plastic detectors on Apollo 17 shows that at energies from ~2 to ~10 MeV/amu, the composition of interplanetary heavy ions is quite different from that of either solar particles or galactic cosmic rays. C+N, Mg+Si, and $Z \geq 20$ are depleted with respect to O, and Li+Be+B are missing. The existence of a peculiar bump in the oxygen energy spectrum is confirmed.

We wish to report the first measurements of the energy spectra of energetic interplanetary heavy ions in which a single detector has been able to span the entire interval from 10 keV/amu to 40 MeV/amu. During times of strong solar activity much of this interval is populated with ions of solar origin whose composition is enriched in heavy elements at the lowest energies but tends at high energies toward rough (but inexact) equality with solar photospheric composition (Price et al., 1973). During solar quiet times the flux of heavy ions is so low that measurements are difficult, requiring the collection of data over long time intervals, with attendant background problems. In the energy intervals ~20 to ~60 MeV/amu and ~40 to ~140 MeV/amu respectively, Mogro-Campero et al. (1973) and O'Sullivan et al. (1973) found that the fluxes of species from C to Fe increased monotonically with energy and that the composition appeared consistent with that characteristic of galactic cosmic rays studied previously at higher energies. Composite data from detectors on two satellites in different parts of the solar system (Hovestadt et al., 1973, on IMP-7; McDonald et al., 1974, on Pioneer 10) have very recently indicated that the quiet-time composition has a strong anomaly between ~2 and ~20 MeV/amu, being enriched in O and N relative to C. At energies between ~0.4 and 1 MeV/amu the spectra of C and O fall steeply with energy, with an O/C ratio of order unity. The origin of the quiet-time particles at E<20 MeV/amu is unknown. Our measurements are thus of some interest.

While on the lunar surface the Apollo 17 astronauts deployed a stack of track-registering Lexan plastic on the shade side of the lunar module for 45.5 hours beginning at 0123 UT, 1972 Dec 12 (Price and Chan, 1973). The stack consisted of 7 sheets, each 125μm x 3.5 cm x 4.5 cm. The top sheet had been coated with a 1000Å layer of Aℓ to screen out ultraviolet light, which would have increased the etch rate along particle tracks in the plastic.

Pieces of the sheets were later etched in 6.25N NaOH solution and etch pits of various lengths were observed along particle trajectories. The etch pit length is approximately a quadratic function of average ionization rate. After irradiating the sheets with a controlled amount of ultraviolet light, a second etch reveals the remainder of the range of each particle. With these two measurements the charge and energy of each particle with Z>2 can be determined. Alpha particles show up only after the UV treatment and re-etch, but can also be identified if they stop within about 10μm of a sheet surface.

Before the mission one region of the top sheet had been irradiated with 3 MeV/amu ^{16}O ions to provide a calibration point. To provide us with very low-energy calibrations, Dr. E. Zinner of Washington University irradiated portions of other sheets with 125 keV/amu ^{19}F ions and with ions of ^{23}Na, ^{40}Ar and ^{56}Fe of energies down to ~6 keV/amu. To view the etch pits for these ions and to determine fluxes at energies below 1 MeV/amu it was necessary to make a silicone rubber replica of the etched sheet, to coat the replica with an Au film, and to observe the replica in a scanning electron microscope.

The open points in Figure 1 are our data for He, O, and Z≳20 at energies from ~10 keV/amu to ~40 MeV/amu, together with our upper limit for Mg+Si at 5 to 9 MeV/amu and several points at energies above 40 MeV/amu from a Lexan stack on the Apollo 16 mission (Braddy et al., 1973). We have also plotted quiet-time He data from McDonald et al. (1973), as well as low-energy data for Z≳20 from Woods et al. (1973), who used glass detectors mounted adjacent to the Lexan stack on Apollo 17. Their data and ours for Z≳20 agree well in the region of overlap.

Table 1 compares our measured abundance ratios with values of Cameron (1973) for the solar system (generally similar to photospheric values) and values of Webber et al. (1972) for galactic cosmic rays at energies of 250 to 850 MeV/amu. Figure 2 compares our oxygen energy spectrum with the quiet-time spectra of Hovestadt et al. (1973) at energies from 0.5 to 8 MeV/amu and of McDonald et al. (1974) at energies from 8 to 50 MeV/amu.

Particles with energy less than 1 MeV/amu. Near the end of the exposure of our Lexan stack outside the lunar module an interplanetary particle fl enhancement occurred. The alpha particle counting rate at 0.5 to 1 MeV/amu on the University of Chicago detector on IMP-7 increased by a factor 5 to 10 over the quiet-time rate (J. A. Simpson, private communication). From Figure 2 we see that at energies below ~1 MeV/amu our oxygen flux is significantly higher than the quiet-time flux of Hovestadt et al. (1973). If we ascribe our excess to contamination with very low-energy solar particles then the entries in the first two lines of Table 1 show that the ratios CNO: He and $[Z \gtrsim 20]$: CNO for those particles are enhanced by factors of ~2 and ~3 with respect to solar values. Thus the systematic pattern of heavy element enrichments observed in solar flares (Price et al., 1973) also characterizes periods when solar activity is only slightly above quiet-time levels. The question of the origin of quiet-time particles at these low energies is thus unfortunately not answered.

Particles with energies of ~1 to 10 MeV/amu. Our oxygen spectrum in Figure 2 reproduces quite well the position and magnitude of the strange "hump" inferred from the composite data of Hovestadt et al. and of McDonald et al. Our simultaneous measurements with a single detector covering the entire energy interval from 0.01 to 40 MeV/amu confirm that there is a source of charged particles of anomalous composition, different from either solar or cosmic ray composition, which at 1 AU dominate the energy spectrum of interplanetary particles at energies of ~2 to ~20 MeV/amu. Since the detector of McDonald et al. was on Pioneer 10 at a distance of several AU, one has to conclude that there is no strong radial gradient of these particles. From Table 1 we see that only the element O, of those we have studied, shows a spectral hump. The elements LiBeB, C+N, Mg+Si, and $Z \gtrsim 20$ are depleted, some by at least an order of magnitude, below their relative abundances in the cosmic rays.

The origin of these particles poses a challenge. Without a drastic revision of solar modulation theory it does not seem possible that such an oxygen hump could exist outside of the heliosphere, since the average energy loss by adiabatic deceleration during solar minimum is expected to be more than 100 MeV/amu for particles entering the heliosphere (Urch and Gleeson, 1973). Nor can one envisage how species as similar as C, N, O could evolve so differently if they originated in the sun. A third possibility, suggested by Ramaty (1973), is that neutral interstellar gas freely leaks into the solar system, becomes ionized by charge exchange with the solar wind or by photoionization, and is somehow accelerated to a few MeV/amu, whereas ionized interstellar gas does not leak in. Although it has been suggested (Jokipii, 1968) that particles can be accelerated at the solar wind boundary, they would also suffer the fate of being strongly modulated before reaching the inner solar system. Yet there is a suggestive correlation with first ionization potential. Both O and N show a hump (Mcdonald et al., 1974), whereas elements with lower ionization potentials - C, Mg, Si, Z≥20 - do not (Table 1). Further, the absence of the secondaries LiBeB (Table 1) supports the idea that the O and N were accelerated locally (though not necessarily within the solar system).

With a large Lexan stack outside the Skylab we hope to be able to establish finite values rather than upper limits for the ratios in Table 1.

We are indebted to E. Zinner for the low-energy calibration samples and to B. J. Teegarden and F. B. McDonald for helpful discussions.

References

Braddy, D., Chan, J.H., and Price, P.B. 1973, Phys. Rev. Letters, 30, 669.

Cameron, A.G.W. 1973, Space Sci. Rev., 15, 124.

Hovestadt, D., Vollmer, O., Gloeckler, G., and Fan, C.Y. 1973, post-deadline paper at 13th International Cosmic Ray Conference, Denver.

Jokipii, J.R. 1968, Ap. J., 152, 799.

McDonald, F.B., Teegarden, B.J., Trainor, J.H., and Webber, W.R. 1974, to be published.

Mogro-Campero, A., Schofield, N., and Simpson, J.A. 1973, Proc. 13th Inter. Cosmic Ray Conf., 1, 140.

O'Sullivan, D., Thompson, A., and Price, P.B. 1973, Nature Phys. Sci. 243, 8.

Price, P.B., and Chan, J.H. 1973, Apollo 17 Preliminary Science Report, NASA Special Publication, in press.

Price, P.B., Chan, J.H., Crawford, H.J., and Sullivan, J.D. 1973, Proc. 13th Inter. Cosmic Ray Conf., 2, 1479 (Univ. of Denver).

Ramaty, R. 1973, Invited talk at Symposium on High-Energy Astrophysics, Tucson, December 6.

Urch, I.H., and Gleeson, L.J. 1973, Ap. Space Sci., 20, 177.

Webber, W.R., Damle, S.V., and Kish, J. 1972, Ap. Space Sci., 15, 245.

Woods, R.T., Hart, H.R., and Fleischer, R.L. 1973, Proc. 13th Inter. Cosmic Ray Conf., 2, 1644 (Univ. of Denver).

Table 1

Anomalous Composition of Low Energy Heavy Ions

Element Ratio	Energy Interval (MeV/amu)	Our Measurement	Solar System Cameron (1973)	Cosmic Rays 250-850 MeV/amu Webber et al. (1972)
CNO:He	0.05-0.5	0.03	0.017	-
[Z≥20]:CNO	0.2-1	0.09	0.027	0.083
LiBeB:CNO	3.4-4.4	<0.059*	$1.1\text{x}10^{-5}$	0.56
[C+N]:O	3.4-4.4	<0.63*	0.72	1.36
[Mg+Si]:O	4.5-8.6	<0.045*	0.096	0.33
[Z≥20]:O	3.7-11	<0.018*	0.046	0.2

*upper limits are 95% confidence values.

Figure Captions

Figure 1. Energy spectra of interplanetary heavy ions recorded in Lexan detector stack on Apollo 17. He data on Pioneer 10 are from McDonald et al. (1974). Note that the scales of ordinate and abscissa are different.

Figure 2. A portion of our oxygen spectrum, compared with data of Hovestadt et al. (1973) and McDonald et al. (1974). Note that the scales of ordinate and abscissa are different.

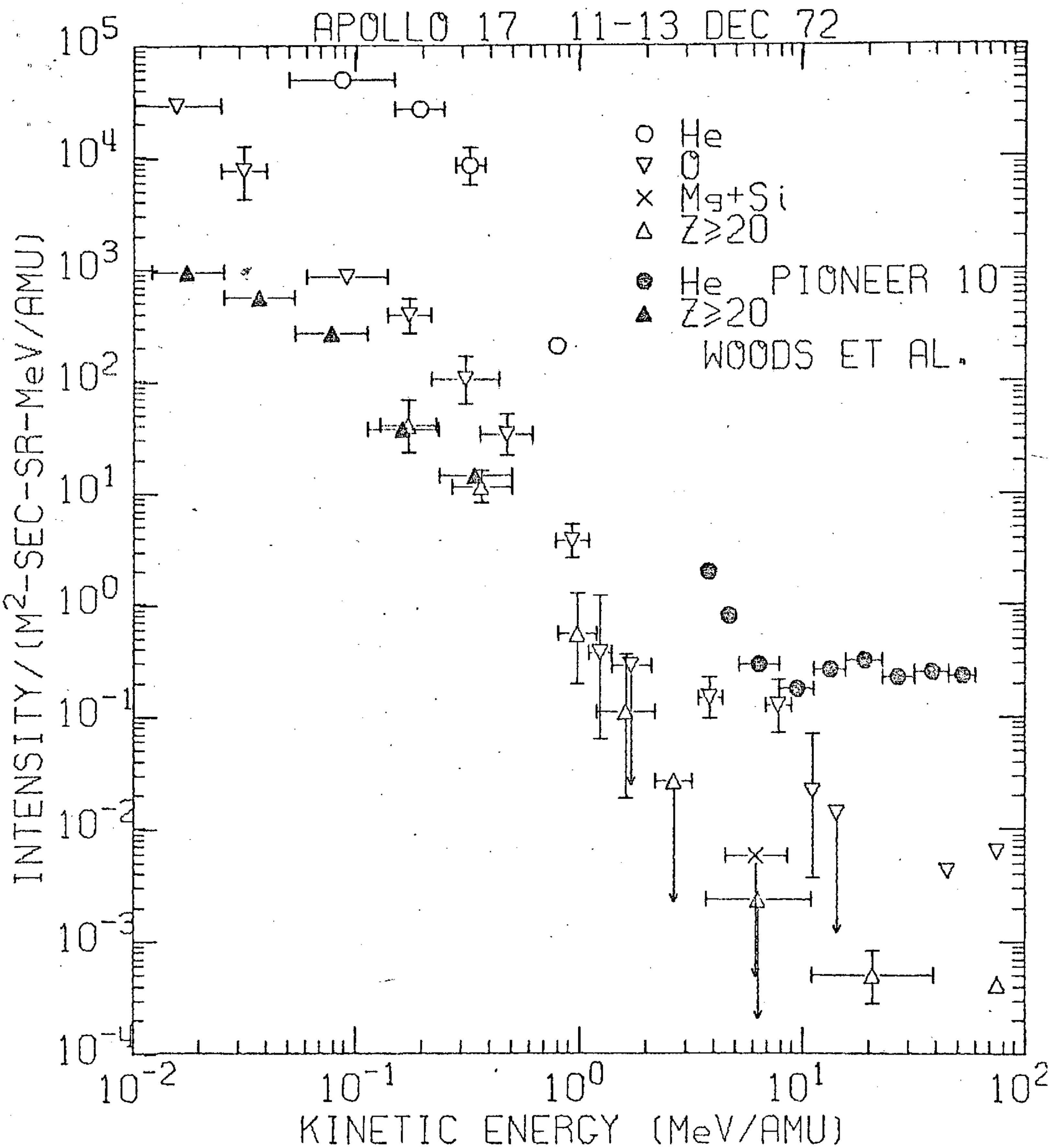

APOLLO 17 11-13 DEC 72
He
O
Mg+Si
Z≥20
He PIONEER 10
Z≥20
WOODS ET AL.
INTENSITY/(M²-SEC-SR-MeV/AMU)
KINETIC ENERGY (MeV/AMU)
10⁵
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻²
10⁻¹
10⁰
10¹
10²

Fig. 1

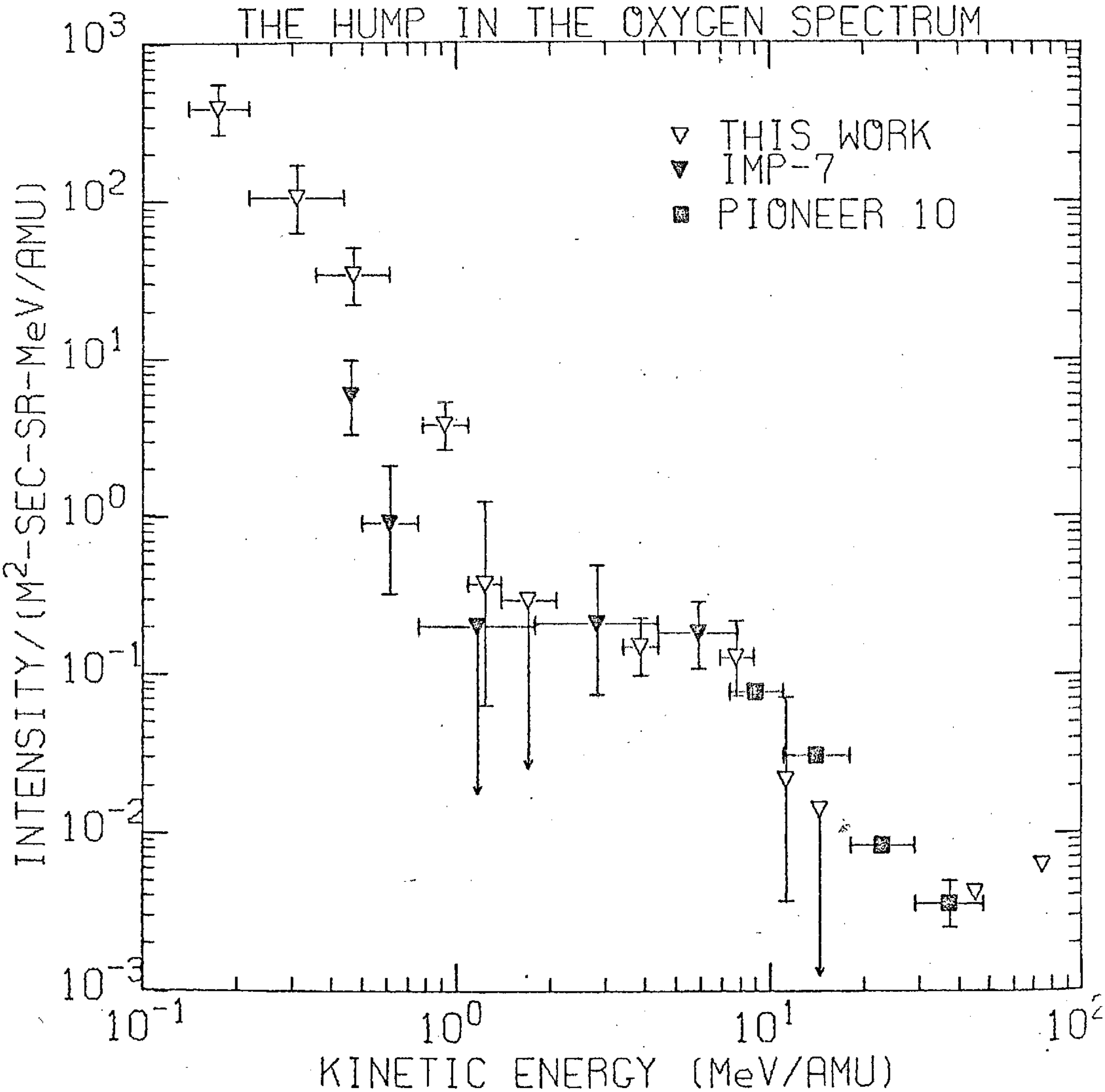

THE HUMP IN THE OXYGEN SPECTRUM
THIS WORK
IMP-7
PIONEER 10
INTENSITY/(M2-SEC-SR-MeV/AMU)
KINETIC ENERGY (MeV/AMU)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-1
10^0
10^1
10^2

Fig. 2

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13th Inter. Cosmic Ray Conf.,
Conference Papers, Vol. 2,
Univ. of Denver, 1973.

LOW ENERGY, HEAVY COSMIC RAY NUCLEI DURING A SOLAR QUIET TIME

R. T. Woods,* H. R. Hart, Jr., and R. L. Fleischer

General Electric Research and Development Center

P. O. Box 8, Schenectady, New York (USA) 12301

Glass detectors were exposed on Apollo 17, 11-13 December, 1972. These detectors yield the energy spectra of heavy nuclei ($Z>10$) in a new range: $0.02<E<0.4$ MeV/amu. Satellite proton data (IMP-7) recently made available indicate that, contrary to the title, this was not a solar quiet time; a small enhancement of 1 MeV protons was observed. For one glass detector exposed in the shade the differential energy flux is found to be $6.33 \times 10^{-5} E^{-2.3\ (+1.2\ -\ 0.9)}$ $(\text{cm}^2\text{-sec-ster-MeV/amu})^{-1}$ for $0.06<E<0.4$ MeV/amu. Detectors of identical glasses exposed facing the sun and facing away from the sun showed a 2:1 ratio in track densities, respectively. These results strongly suggest that these nuclei are solar in origin.

1. Introduction. The primary objective of the General Electric portion of the Apollo 17 cosmic ray experiment was to measure the elemental abundances, energy spectra and, hopefully, to infer the origin of heavy low energy nuclei at solar quiet time. Three varieties of glass solid state track detectors were exposed on the lunar surface for 45.5 hours 11-13 December, 1972. The detectors were arrayed in two groups, one facing the sun, one facing away from the sun. In December 1972 solar activity was approaching the predicted 1975 minimum and should have been lower than at any time since 1966. As a result the solar modulation of galactic cosmic rays should also have been approaching its minimum. Characteristically, the fluxes of these galactic particles have been observed to decrease with decreasing energy in the range from a few hundred MeV/amu down to the lowest energies measured, ~40 MeV/amu for heavy nuclei (1). Solar flare particles in contrast are found in general to decrease in abundance with increasing energy (2) and, specifically for heavy nuclei in the energy range of this experiment (1,3,4). One of our keys for deciding the solar or galactic nature of low energy nuclei is thus the slope of the energy spectrum.

By exposing two detectors of the same type, one facing the sun and one facing away from the sun, we can assess any existing anisotropy. Furthermore, an anisotropy strongly peaked in the sun direction would be indicative of particles of solar origin; we thus have a second key for deciding the solar or galactic nature of the nuclei.

2. Experimental. The detectors consisted of nine pieces of glass of the three following types: fused quartz, a GE phosphate glass (#1457; 6.3 wt % P_2O_5: 11.0% BaO: 9.3% Ag_2O: 8.5% K_2O: 8.2% Al_2O_3), and a lead phosphate glass furnished by D. Lal (77.4% Pb_3PO_4: 10% Mn_3PO_4: 12.6% $FePO_4$, melted in a mullite crucible - D. Lal, personal communication).

Particle tracks were revealed under carefully controlled etching conditions with a fixed temperature bath, a fixed etchant stirring rate, and fresh etchant at each separate stage of etching. The general chemical attack rate, V_g, was measured first, using control samples, by three methods: the rate of motion of a right angled edge relative to fixed markers in the glass, the attack rate inferred from cone angle and track diameter measurements on individual tracks, and from the thickness change of glass plates with parallel faces. When a flight sample was etched, simultaneous and independent measurement of the general attack rate was made and checked with a predicted etch rate for consistency. The GE 1457 glass, for example, was etched in 48% HF for 5.0 min. at 29.3°C to remove 0.5×10^{-4} cm of glass.

Track measurements were made using a Leitz Ortholux microscope at a nominal magnification of 1000 times and a filar eyepiece with a movable hairline. The threshold capability of the eyepiece was checked by an independent experiment. In this experiment, a group of identical glass samples of glass microscope slides were irradiated with Cf^{252} fission fragments at normal incidence. Samples were then etched under identical etch conditions but in successive increments of 15 sec. intervals in 5.7% HF at 22.3°C. Track diameter measurements allowed a plot of track diameter vs. etch time to be constructed. For the range of track lengths examined, linearity is expected in track diameters since there is very little change in the cone angle. A straight line was obtained which implied that reliable dimension measurements are possible down to a lower optical limit of 0.35×10^{-4} cm.

Individual particle ranges were then calculated using the etched track length and the amount by which the track is rounded out. The differential energy spectrum was obtained starting with the measured particle range distribution. Particle ranges were grouped in length bins, and equivalent energies corresponding to the lower and upper limits were obtained using range-energy tables (5) for Fe ions in aluminum for the GE 1457 glass, for example, since this glass is closely similar to Al in its stopping power. This approximation introduces negligible additional errors. The energy between these two limits was evaluated so that the same number of particles within that bin fall on either side of the energy representing the bin. It was assumed for the purposes of calculation that all particles registered in GE 1457 glass were from the iron group with a cone angle of ~5°. This glass is sensitive to ions as light as neon and thus may contain tracks from ions lighter than those in the iron peak. Low energy calibration measurements are in progress and will supplement existing higher energy calibrations that give cone angles of 30-35°, 10°, and 5° for Ne, Ar and Fe respectively (3). It is intended that the different elemental constituants can be identified in this manner.

3. Results. The following table and figure summarize the results for the GE 1457 phosphate glass detector which was exposed in the shade. The resulting energy spectrum extends from ~0.02 to ~0.4 MeV/amu. Visually fitting the three highest energy data points ($0.06<E<0.4$ MeV/amu) with a power law in kinetic energy the flux is given by $6.33 \times 10^{-5} E^{-2.3}$ (+1.2 - 0.9) $(cm^2\text{-sec-ster-MeV/amu})^{-1}$.

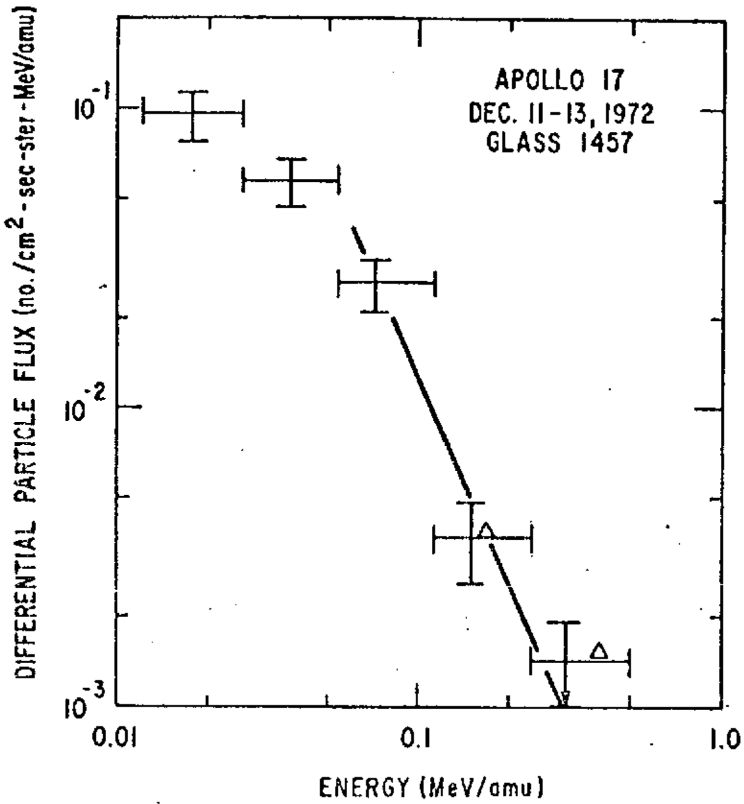
Track Data in the Apollo 17 GE 1457 Phosphate Glass

Particle Range Interval (10^{-4} cm)	Number† Stopping	Energy* Interval (MeV/amu)	Differential** Flux J $(cm^2\text{-ster-sec-MeV/amu})^{-1}$
.5 – .85	31	.0121 – .0255	$9.56 \pm .17 \times 10^{-2}$
.85 – 1.43	38	.0255 – .0537	$5.66 \pm .92 \times 10^{-2}$
1.43 – 2.41	37	.0537 – .1130	$2.66 \pm .43 \times 10^{-2}$
2.41 – 4.05	11	.1130 – .2370	$3.73 \pm 1.12 \times 10^{-3}$
4.05 – 6.85	9 (6)	.2370 – .5000	$1.44 \pm .48 \times 10^{-3}$

†The number in brackets is the number of tracks which have not rounded. This means the particle stopped at a depth in the glass greater than the track's measured length. It was assumed that some of the 6 sharp tracks in the length interval 4.05 - 6.85 x 10^{-4} cm could round out in the next larger length interval - hence the arrow on the uppermost data point in the figure.

*Range-Energy tables (Northcliffe & Schilling (5)) were used to determine energy intervals.

**For this detector: exposure time = 45.5 hrs.; effective solid angle = 1.55 ster; area scanned = 9.38×10^{-2} cm^2; $J = (N/\Delta E)\ 4.2 \times 10^{-5}$ $(cm^2\text{-sec-ster-MeV/amu})^{-1}$.



Differential Energy Spectrum of Heavy Cosmic Ray Nuclei at the Moon 11-13 December, 1972 inferred from the distribution of stopping depths in GE 1457 phosphate glass. The two points marked by the Δ symbol are the lowest energy Fe data taken from Figure 1 of Price and Chan (6).

From the lead phosphate glass detectors track densities for the sun and shade exposed portions are 1025 ± 103 cm^{-2} and 483 ± 60 cm^{-2} respectively, a ratio of 2.12 (±.34). The differential track range distribution for each portion indicate similar steeply falling spectra with increasing energy.

4. Discussion. The results show at the higher energies ($0.06 < E$ (MeV/amu) < 0.4) for the shade exposed GE phosphate glass a steep spectral shape which can be represented by a power law in kinetic energy:

$$6.33 \times 10^{-5}\, E^{-2.3(+1.2\ -0.9)}$$

At lower energies the spectrum flattens. Qualitatively, the shape of the spectrum at higher energies is similar to that measured for single solar flare events (1,3,4,7), the first three references referring to analysis of the April 17, 1972 solar flare observed by the Apollo 16 cosmic ray experiment. The spectral shape at higher energies is also qualitatively similar to that observed for the cumulative effect of many flares over 2½ years at a time of maximum solar activity (8-10). This aspect alone suggests a solar origin for these low energy heavy cosmic rays. The absolute flux level at any given energy is much lower in the Apollo 17 spectrum than in the Apollo 16 spectrum. This is consistent with the satellite monitors which showed orders of magnitude more protons during the Apollo 16 experiment than during the Apollo 17 experiment. A significant fact is that steep spectra are observed in both experiments even though solar modulation has presumably changed between these events. For the lead phosphate glass detectors the two results of steeply falling energy spectra with increasing energy for both sun and shade exposed portions, and the approximate 2:1 ratio in track densities for the sun and shade portion, respectively, also indicate a solar origin for these particles.

We must ask whether our conclusion that the heavy particles are solar in origin, is consistent with other observations of the actual solar activity. The answer is yes. Roughly midway during our exposure the IMP-7 proton counter showed a 50 fold increase and typical flarelike decay in the 0.5 - 1.8 MeV count rate (J. Simpson, personal communication), apparently associated with a IF flare on 12 December, 1972. With a slight extrapolation of our energy spectra to 0.7 MeV nucleon we infer a proton to iron ratio ~10,000/1 which is consistent with our result at the same energy for the 17 April 1972 flare (5000/1).

5. Conclusions. From 80 to 400 KeV/amu during the period 11-13 December, 1972 the differential flux of heavy cosmic ray nuclei decreased roughly as (kinetic energy)$^{-2}$ with the flux from the solar direction being twice that from the antisolar direction. These data plus the satellite proton counter observation of a 50 fold increase in flux during the exposure time imply that these nuclei were solar in origin.

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References:

1. Braddy, D., J. Chan, and P. B. Price, Charge States and Energy-Dependent Composition of Solar-Flare Particles, Phys. Rev. Lett., 30, 669-671, 1973.

2. Biswas, S., and C. E. Fichtel, Composition of Solar Cosmic Rays, Space Science Reviews, 4, 709-736, 1965.

3. Fleischer, R. L., and H. R. Hart, Jr., Enrichment of Heavy Nuclei in the April 17, 1972 Solar Flare, Phys. Rev. Lett., 30, 31-34, 1973.

4. Burnett, D., C. Hohenberg, M. Maurette, M. Monnin, R. Walker, and D. Woolum, Solar Cosmic Ray, Solar Wind, Solar Flare, and Neutron Albedo Measurements, Apollo 16 Preliminary Science Report, NASA SP-315, 15-19--15-32, 1972.

5. Northcliffe, L. C., and R. F. Schilling, Range and Stopping Power Tables for Heavy Ions, (Texas A&M, College Station, Texas, 1970), and Nucl. Data, Sect. B, 7, 233ff, 1970.

6. Price, P. B., and J. H. Chan, The Nature of Interplanetary Heavy Ions with $0.1<E<40$ MeV/nucleon, Apollo 17 Preliminary Science Report (to be published).

7. Lin, R. P., et. al., Solar Flare Injection and Propagation of Low-Energy Protons and Electrons in the Event of 7-9 July 1966, Solar Physics, 4, 338-360, 1968.

8. Fleischer, R. L., H. R. Hart, Jr. and G. M. Comstock, Very Heavy Solar Cosmic Rays: Energy Spectrum and Implications for Lunar Erosion, Science, 171, 1240-1242, 1971.

9. Crozaz, G., and R. M. Walker, Solar Particle Tracks in Glass from the Surveyor 3 Spacecraft, Science, 171, 1237-1239, 1971.

10. Price, P. B., I. Hutcheon, R. Cowsik, and D. J. Barber, Enhanced Emission of Iron Nuclei in Solar Flares, Phys. Rev. Letters, 26, 916-919, 1971.

* also at State University of New York at Albany.

(Submitted, Astrophysical Journal)

APOLLO 17

COSMIC RAY EXPERIMENT:

THE NATURE OF INTERPLANETARY HEAVY NUCLEI

IN THE ENERGY RANGE 0.05 to 5.0 Mev/amu

by

R. T. Woods*, H. R. Hart, Jr., and R. L. Fleischer

General Electric Corporate Research and Development Center

Schenectady, New York

*also at State Univ. of New York at Albany

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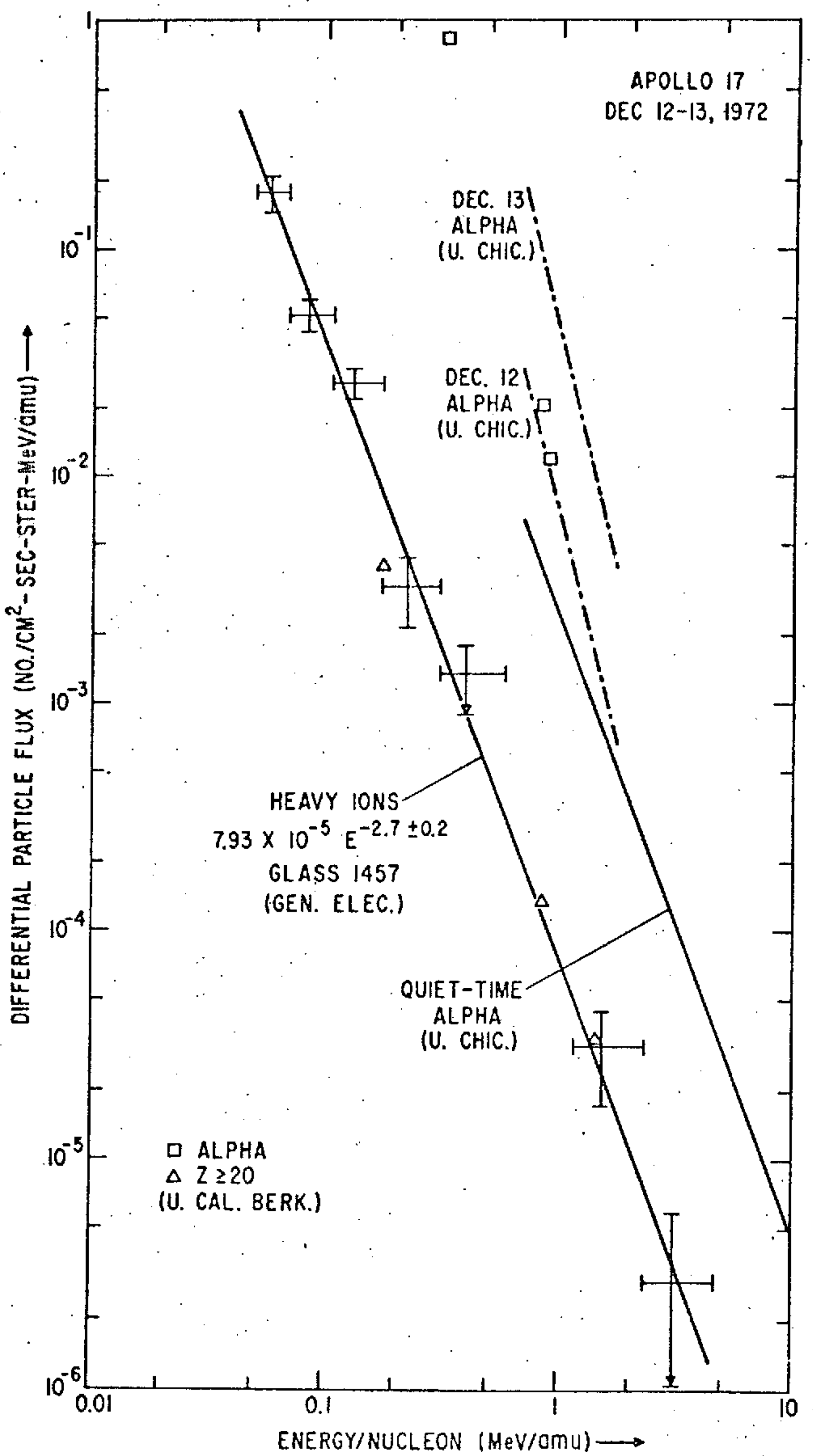
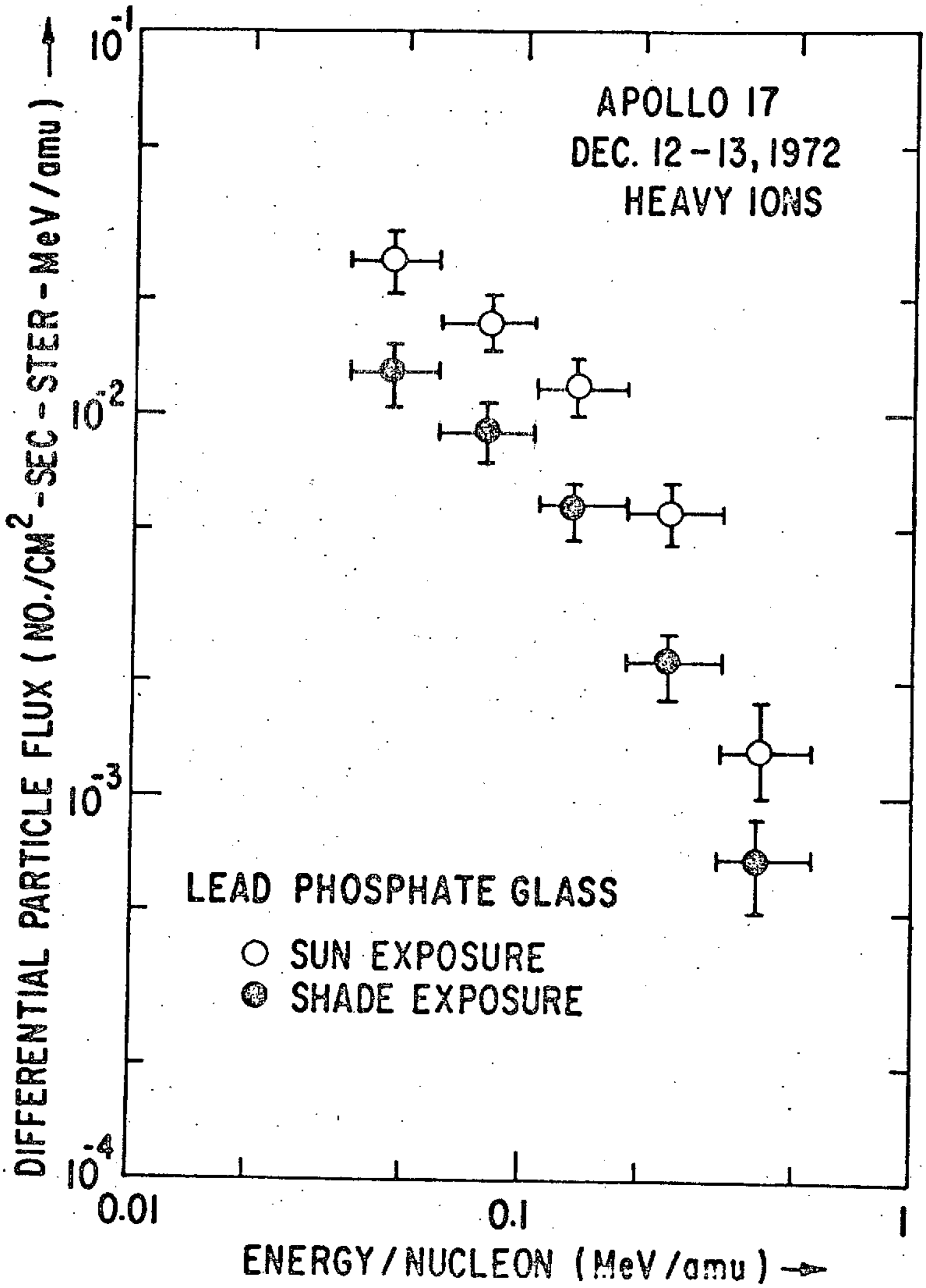
Three varieties of glass solid state track detectors on the General Electric portion of the Apollo 17 cosmic ray experiment were exposed to interplanetary heavy ions while the detectors were fixed relative to the lunar surface from 0123 Dec. 12 to 2253 Dec. 13, 1972. The detectors were arrayed in two groups, one of which was exposed facing the sun, while, simultaneously, the other was exposed in the shade facing away from the sun. In the energy range of 0.05 to 5.0 Mev/amu the differential flux of heavy cosmic ray nuclei was observed to be a straight line power law spectrum roughly of the form E^{-3}, characteristic of solar particles, where E is the kinetic energy in Mev/amu. This heavy ion spectrum was deduced from shade-exposed GE 1457 phosphate glass detectors and is shown in Fig. 1. The particle discrimination capability of these solid state track detectors along with individual track parameter measurements show that these heavy nuclei consisted mostly of Fe. Also shown in Fig. 1 is the spectrum for heavy ions with $Z \geqslant 20$ (denoted by Δ in Fig. 1; P. B. Price, et. al., Univ. Calif., Berkeley) deduced from plastic detectors also having a shade exposure. These data are consistent. During the time of the experiment the sun was only slightly active, deduced from both ground-based observations of solar activity and satellite measurements of particles in interplanetary space. This can be seen by comparing the alpha spectra measured by an instrument on the IMP 7 satellite (J. A. Simpson, et. al., Univ. Chicago) for typical "quiet-time" periods and for Dec. 12 and Dec. 13, 1972--these latter two spectra being only slightly higher than quiet-time levels. The Fe/α ratio at ~1 Mev/amu is enhanced by a factor of 10 above solar abundances consistent with enhancements measured for low energy solar flare particles. Lead phosphate glass detectors which had both sun and shade exposures made possible a comparison between energy spectra for particles from the two directions. These two spectra are shown in Fig. 2. The spectral shapes are identical over the same energy range, consistent with current ideas that energy loss processes in the interplanetary medium are negligible. The sun spectrum is displaced upward from the shade spectrum by a factor of 2. This observation of solar-related anisotropy, along with the E^{-3} spectrum and factor of 10 enhancement in the Fe/α ratio, yields the strong inference that these heavy ions are solar in origin.

Fig. 1. The final differential energy spectrum for heavy ions is shown. The spectrum was deduced from the GE 1457 phosphate glass exposed in the shade on the lunar surface during the Apollo 17 cosmic ray experiment. The spectral form over an energy interval of 0.05 to 5.0 Mev/amu is given where E is the particle kinetic energy in Mev/amu. Also shown are spectra deduced from plastic detectors having the same type of exposure as the GE 1457 phosphate glass for ions with $Z \geqslant 20$ (Δ) and alpha particles ($\square$), (P.B. Price, et. al., Univ. Calif., Berkeley). Alpha spectra measured by instruments on the IMP 7 satellite are indicated for Dec. 12, Dec. 13, and typical "quiet-time" periods, (J. A. Simpson, Univ. Chicago).



APOLLO 17
DEC 12-13, 1972
DEC. 13
ALPHA
(U. CHIC.)
DEC. 12
ALPHA
(U. CHIC.)
HEAVY IONS
7.93 X 10^-5 E^-2.7 ±0.2
GLASS 1457
(GEN. ELEC.)
QUIET-TIME
ALPHA
(U. CHIC.)
□ ALPHA
Δ Z ≥20
(U. CAL. BERK.)
DIFFERENTIAL PARTICLE FLUX (NO./CM²-SEC-STER-MeV/amu) →
ENERGY/NUCLEON (MeV/amu) →
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0.01
0.1
1
10

Fig. 2. Shown here are the heavy ion spectra deduced from the Apollo 17 lead phosphate glass detectors exposed facing the sun (sun exposure) and facing away from the sun (shade exposure). The spectra show a 2:1 ratio of the number of particles detected by the sun and shade-exposed detectors, consistent with solar origin of these particles. The spectra have the same spectral shape over the entire energy range. Spectra have not been corrected for particle range deficit and change in effective solid angle factor as a function of energy. However, with the correction for particle range deficit the shade spectrum is consistent with the heavy ion spectrum deduced from the shade-exposed GE 1457 phosphate glass.


APOLLO 17
DEC. 12-13, 1972
HEAVY IONS
LEAD PHOSPHATE GLASS
SUN EXPOSURE
SHADE EXPOSURE
DIFFERENTIAL PARTICLE FLUX (NO./CM^2-SEC-STER-MeV/amu) →
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.01
0.1
1
ENERGY/NUCLEON (MeV/amu) →

Publications resulting from this work:

1. R. T. Woods, H. R. Hart, Jr. and R. L. Fleischer, "Low Energy, Heavy Cosmic Ray Nuclei During a Solar Quiet Time," paper #299, 13th International Cosmic Ray Conference, Denver, Colorado, August 17-30, 1973.

2. R. T. Woods, H. R. Hart, Jr. and R. L. Fleischer, "Apollo 17 Cosmic Ray Experiment: The Nature of Interplanetary Heavy Nuclei in the Energy Range 0.05 to 5.0 Mev/amu," (to be submitted to Astrophysical Journal).

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