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FINAL REPORT

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LUNAR SURFACE COSMIC RAY EXPERIMENT

Professor P. B. Price
Principal Investigator

Space Sciences Laboratory Series 15, Issue 9

February 7, 1974

UNIVERSITY OF CALIFORNIA, BERKELEY

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Lunar Surface Cosmic Ray Experiment

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The University of California cosmic ray experiment on Apollo 16 has had a significant impact on our understanding of both galactic cosmic rays and solar flare particles. The published papers attached to this final report describe the experiment, equipment, data processing techniques, and operational history.

We wish to distill the findings reported in the four papers into the following major new results:

1. The composition of heavy ions in interplanetary space at energies between ~30 and ~130 MeV/nucleon is the same, within experimental errors, as that previously determined by other workers at higher energies and identified with galactic cosmic rays. Adiabatic deceleration as these particles enter the solar system could account for the absence of any change of composition that might be expected of low-energy particles due to ionization loss and spallation.

2. The ability of a Lexan stack to determine simultaneously the energy spectra of major elements from He up to Fe in the energy interval 0.2 to 30 MeV/nucleon has revealed systematic changes in the composition of solar flare particles as a function of energy. Compared with the composition of the solar photosphere, the particles emitted during a solar flare are enriched in heavy elements by an amount that increases with atomic number (up to a factor $\sim 10^2$ for Fe compared with He at 0.2 MeV/nucleon) and decreases with increasing energy.

3. Heavy ions emitted in a solar flare appear to be completely stripped of electrons and are thus not in charge equilibrium at the time of acceleration and release from the sun.

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Composition of Galactic Cosmic Rays with $30 < E < 130$ MeV/Nucleon

A STACK of track-recording plastic detectors was exposed outside the Apollo 16 lunar module so that we could study the chemical composition, energy spectra and origin of interplanetary heavy ions with $0.2 \lesssim E \lesssim 150$ MeV/nucleon. The relative abundances of secondary nuclei such as LiBeB and the elements $17 \leq Z \leq 25$ as a function of energy should be directly related to the galactic cosmic ray contribution because they are extremely rare in the Sun and in solar flare particles.

On the second day of the Apollo 16 mission (April 18, 1972) a weak solar flare produced a temporary background of energetic particles that exceeded the quiet-time flux at energies below ~ 30 MeV/nucleon. An analysis of the composition and energy spectra of these solar flare particles has been presented elsewhere[1]. Here we discuss the particles with $E > 30$ MeV/nucleon and show that they are of galactic origin. Our measurements are the first to be made at energies below ~ 150 MeV/nucleon on elements as heavy as Fe. They are particularly interesting in light of other recent observations that the composition of cosmic rays changes with energy in the interval ~ 2 to ~ 70 GeV/nucleon (refs. 2–6).

Details of the experiment are given in NASA's Apollo 16 Preliminary Science Report[7]. We have analysed tracks of cosmic rays with $Z \geq 6$ that stopped in a stack of 40 cellulose triacetate sheets each 16.5 cm × 11.5 cm in area and 200 μm thick. The stack was covered with a 50 μm silvered Teflon sheet, the purpose of which was to minimize absorption of visible sunlight and maximize infrared emission. Colour-changing indicators confirmed that the temperature of the stack was successfully kept below 70° C throughout the mission. At such temperatures tracks are relatively resistant to thermal annealing.

Two sections, each 20 cm² in area, were cut from the stack and etched at 40° C for 20 and 30 h, respectively, in a solution containing seven parts by volume of 6.25 N NaOH and five parts of 12.5% NaClO. We identified tracks of charged particles by measuring etch pit lengths and residual ranges by the method reviewed in ref. 8. The Fe and Si peaks were easily recognizable in the data and were used to determine the constants a and n in the relation between track etch rate V_t and ionization rate J

$$V_t = aJ^n \tag{1}$$

where

$$J = 10^{-4}(Z^{*2}/\beta^2)[\ln(\beta^2/(1-\beta^2)) - \beta^2 + K] \tag{2}$$

K is a constant ≈ 20 and Z^* and β are the effective charge and velocity of the ion. The values $a = 0.0143$ μm h^{-1} and $n = 2.36$ were used to calculate charges from the etch rate data.

We analysed tracks of about 360 stopping nuclei within energy intervals ranging from 18 to 110 MeV/nucleon for the CNO group to 50 to 220 MeV/nucleon for the Fe group. Fig. 1 shows the overall abundance distribution corrected for scanning efficiency and for the size of the energy interval sampled but not corrected for the systematically increasing mean energy with increasing Z.

Because the fluxes are increasing with energy (Fig. 2), the abundance distribution in Fig. 1 slightly favours heavy elements over light elements but still looks remarkably similar to charge distributions obtained at energies up to a few GeV/nucleon by others[9,10]. For example, the observed proportion of nuclei with $17 \leq Z \leq 25$ (which are predominantly spallation products) relative to Fe and Ni is 1.51 ± 0.3, which is consistent with values obtained for galactic cosmic rays at $E > 250$ MeV/nucleon

Table 1 Abundance Ratios

Ratio	Our result	ΔE (MeV/N)	Webber *et al.*[10] 250–850 MeV/N	Webber *et al.*[10] >850 MeV/N
CNO/ $23 \leq Z \leq 28$	17.3 ± 5.8	60– 90	16.6	17.56
CNO/ Fe+Co+Ni	25.0 ± 8.0	60– 90	22.8	21.3
$10 \leq Z \leq 14$/ Fe+Mg+Si	5.6 ± 1.5	60–100	5.76	5.07
Ne+Mg+Si/ Fe+Co+Ni	4.2 ± 1.1	60–100	5.07	4.58
$17 \leq Z \leq 25$/ Fe+Co+Ni	1.50±0.5 1.52±0.6	60–100 100–130	1.15	0.87

(refs. 9 and 10) but is far higher than the value ~ 0.2 obtained for solar flare particles[11]. We can thus make a strong case that most interplanetary particles with $E \gtrsim 30$ MeV/nucleon are of galactic rather than solar origin.

In Fig. 2 we have plotted fluxes of the various charge groups in two energy intervals for which the counting statistics are best. The curve in the Figure represents the He flux measured by Garcia-Munoz *et al.*[12] during May–July 1972, scaled down by a factor 400, the approximate flux ratio of He to $[23 \leq Z \leq 28]$ observed at energies above ~ 200 MeV/nucleon. The shape and magnitude of our spectrum for $23 \leq Z \leq 28$ seem to be reasonably consistent with what would be expected if the composition is independent of energy.

Further evidence that the composition does not change with energy below ~ 1 GeV/nucleon is given in Table 1. Column 2 gives our abundance ratios evaluated in the energy interval shown in column 3, and columns 4 and 5 give the ratios at 250 to 850 MeV/nucleon and at > 850 MeV/nucleon determined by Webber *et al.*[10]. The ratios are independent of energy within counting statistics.

This result can be taken as supporting evidence that cosmic rays in the inner Solar System with energies below 100 MeV/nucleon have suffered adiabatic deceleration from energies of several hundred MeV/nucleon before they entered the Solar

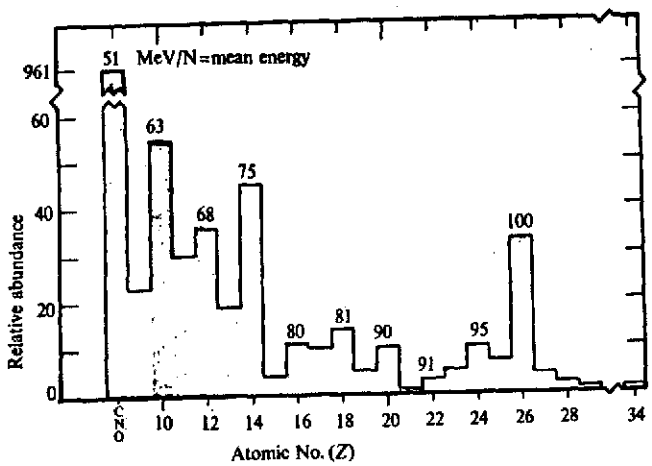

Fig. 1 Relative fluxes per unit energy for nuclei stopping in the stack. The numbers in the graph indicate the mean energies to which the fluxes refer.

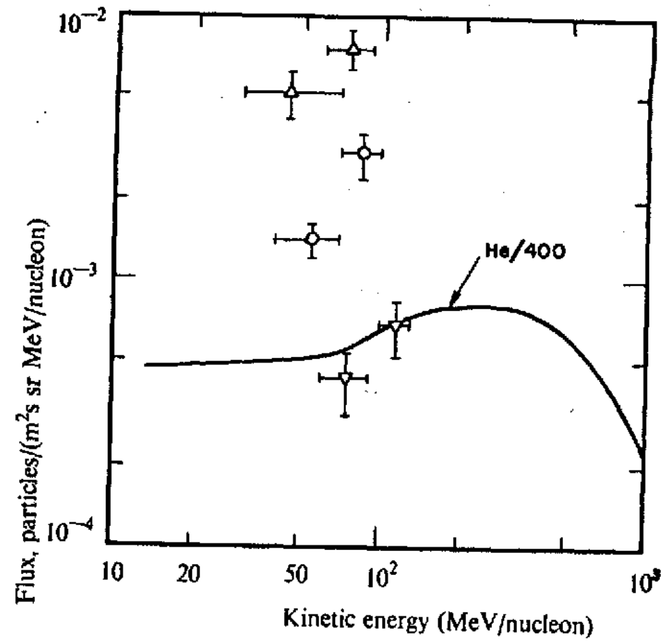

Fig. 2 Energy spectra of low-energy cosmic rays during April 16–23, 1972. The curve represents the He spectrum observed[12] during May–July 1972 but scaled down by the abundance ratio He/$[Z > 23]$. Δ, CNO; $\bigcirc$; $10 \leq Z \leq 14$; ∇, $23 \leq Z \leq 28$.

System. At ~ 100 MeV/nucleon the cross-section for fragmentation of Fe into Mn and Cr rises to several hundred millibarns and one would expect the ratio of (Mn+Cr)/Fe to increase accordingly for cosmic rays that had that energy outside the solar system.

Our measurements thus show that the marked changes in the relative proportions of [CNO]/[Fe+Ni] and of $[17 \leq Z \leq 25]$/[Fe+Ni] observed at energies above ~ 1 GeV/nucleon (refs. 2 to 6) are absent at energies between ~ 1 GeV/nucleon and ~ 30 MeV/nucleon.

We thank E. Kee, H. O'Donnell, D. Molloy, E. Ronaldson and Joan Steel for their assistance. The research was supported in part by NASA.

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[1] Braddy, D., Chan, J. H., and Price, P. B., *Phys. Rev. Lett.*, **30**, 669 (1973).
[2] Juliusson, E., Meyer, P., and Müller, D., *Phys. Rev. Lett.*, **29**, 445 (1972).
[3] Ormes, J. F., and Balasubrahmanyan, V. K., *Nature Physical Science*, **241**, 95 (1973).
[4] Smith, L. H., Buffington, A., Smoot, G. F., Alvarez, L. W., and Wahlig, M. A., *Astrophys. J.*, **180**, 987 (1973).
[5] Webber, W. R., Lezniak, J. A., Kish, J. C., and Damle, S. V., *Nature Physical Science*, **241**, 96 (1973).
[6] Balasubrahmanyan, V. K., and Ormes, J. F., *NASA GSFC X-661-72-447* (1972).
[7] Price, P. B., Braddy, D., O'Sullivan, D., and Sullivan, J. D., *NASA Special Publication*, SP-315, section 15, p. 11 (1973).
[8] Price, P. B., and Fleischer, R. L., *Ann. Rev. Nucl. Sci.*, **21**, 295 (1971).
[9] Cartwright, B. G., Garcia-Munoz, M., and Simpson, J. A., in *Proc. Twelfth Intern. Conf. Cosmic Rays, Hobart, 1971* (edit. by Fenton, A. G., and Fenton, K. B.), **1**, 215 (Univ. Tasmania, 1972).
[10] Webber, W. R., Damle, S. V., and Kish, J., *Astrophys. Space Sci.*, **5**, 245 (1972).
[11] Crawford, H. J., Price, P. B., and Sullivan, J. D., *Astrophys. J. Lett.*, **175**, L149 (1972).
[12] Garcia-Munoz, M., Mason, G. M., and Simpson, J. A., *Astrophys. J.* (in the press).

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Charge States and Energy-Dependent Composition of Solar-Flare Particles*

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During a weak solar flare, energy spectra of He, O, and Fe from 0.2 to ~30 MeV per nucleon were measured with glass and plastic detectors exposed on the Apollo 16 spacecraft. The spectra were very steep and the abundance ratios Fe/O and O/He decreased rapidly with energy, approaching solar atmospheric ratios at energies above ~5 MeV per nucleon. The shapes of the rigidity spectra suggest that the ions were completely stripped while being accelerated.

Results of several recent experiments have indicated that heavy nuclei are present in higher than solar proportions in low-energy solar-flare particles.[1-6] Until now the regime of charge or energy studied with a given detector has been limited, and various assumptions have had to be made in order to infer a heavy-element enhancement.[7] Further, it has not been possible with electronic detectors on satellites to identify heavy particles at energies below a few MeV per nucleon. This is a region where interesting peculiarities in composition might be expected, because at low energies ions in charge equilibrium should have charge/mass ratios that vary with charge and velocity.

In the lunar-surface cosmic-ray experiment[8] on Apollo 16 we have been able to measure fluxes of solar particles covering 9 orders of magnitude of intensity and to identify major elements from He to Fe at energies down to 0.2 MeV per nucleon that originated in the flare on 17 April 1972. Our results provide decisive evidence that the composition of solar-flare particles changes with energy, with the Fe/O and O/He ratios smoothly decreasing with energy.

Silica glass was used to record tracks of nuclei with $Z \gtrsim 18$, about 90% of which were left by Fe nuclei. The glass was etched sequentially from 1 to 12 h in a 5%-HF solution. Plastic replicas of the surface were made after each hour and examined by optical and scanning electron microscopy. For calibration, control samples were bombarded with Ar, Ti, Fe, and Kr ions of 2 to 10 MeV per nucleon and processed together with the actual detector. Atomic numbers and energies were determined from shapes and sizes of replicated etch pits.

Multilayer stacks of Lexan were used to record tracks of nuclei with $Z > 1$. A three-stage process consisting of a NaOH etch, ultraviolet irradiation, and a re-etch[9] produced tracks whose geometry allowed atomic numbers and energies to be determined. To permit a continuous sampling of He tracks at energies below 1 MeV per

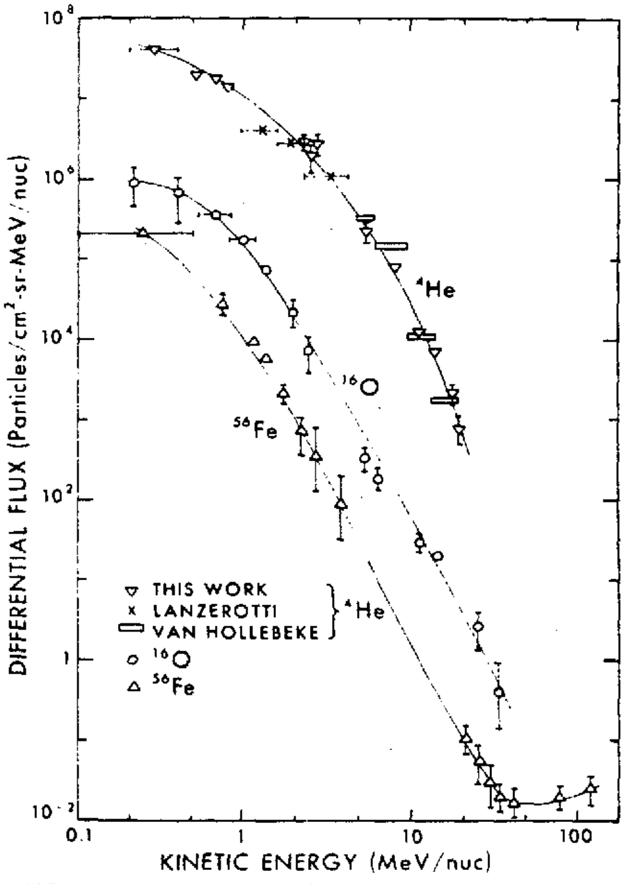

FIG. 1. Energy spectra of He, O, and Fe summed over the week of 16 to 23 April 1972 during which a weak flare occurred. The α particle data of Lanzerotti and of van Hollebeke were obtained with electronic detectors on satellites. To get the average flux per second for the flare particles, divide the ordinate by 8×10^4 sec. (The flare lasted about 1 day.) To get the flux per second for the Fe nuclei of energy greater than ~40 MeV per nucleon, divide the ordinate by 6×10^5 sec. (Being galactic in origin, they entered the detector during the entire collecting interval of 167 h.)

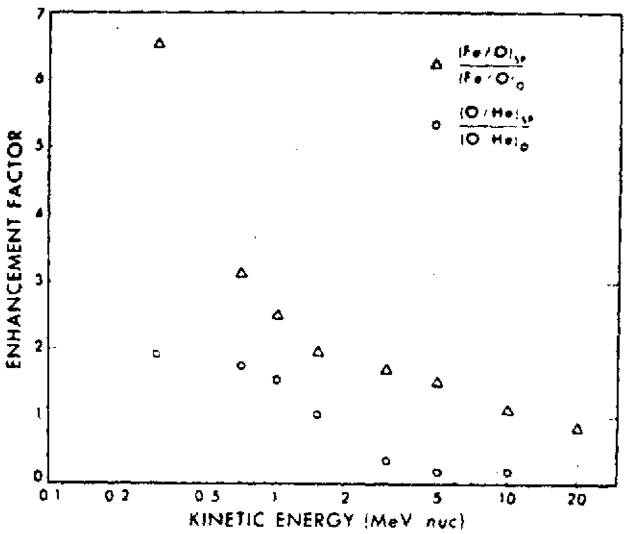

FIG. 2. Ratios of Fe/O and O/He as a function of energy. The ratios are normalized to solar abundances assumed to have the proportions He:O:Fe = 92:1:0.03. The absolute level of the ratios is uncertain by a multiplicative factor of $\sim \pm 1.5$.

nucleon, the top Lexan sheet was embedded in epoxy, ground at a shallow angle, then exposed to uv radiation and etched.

Figure 1 shows the energy spectra of the three abundant elements He, O, and Fe integrated over the flare. Unpublished He data of Lanzerotti and of van Hollebeke for the same flare are included for comparison. The agreement is excellent. The rapid change of composition with energy is plotted in Fig. 2. At energies above ~5 MeV per nucleon the He:O:Fe ratio is ~125:1:0.03, which is not significantly different from current estimates of the photospheric abundances.

These results compel us to reassess the notion[10] that chemical abundances of solar-flare particles mirror the composition of the solar atmosphere. It may be reasonably safe to assume that solar abundance ratios of elements with nearly the same Z can be inferred from solar-particle abundances at the highest energies for which data exist. Examples of interest to the astronomer would be the ratios Ne/Mg and Ar/Si, because spectroscopic data for Ne and Ar in the photosphere do not exist. However, until we have a satisfactory theory that accounts for heavy-element enhancements at low energies, we must be cautious about equating the entire abundance pattern of solar particles from He to Fe to the pattern in the sun. Possibly this equality holds for long-term averages at high energies.

We turn now to the question of the charge states of the solar-flare particles. Figure 3 shows the rigidity spectra of He, O, and Fe, computed from the data in two ways: (a) assuming the ions were completely stripped, using $R = m_p c^2 \beta (A/Z)/e$,

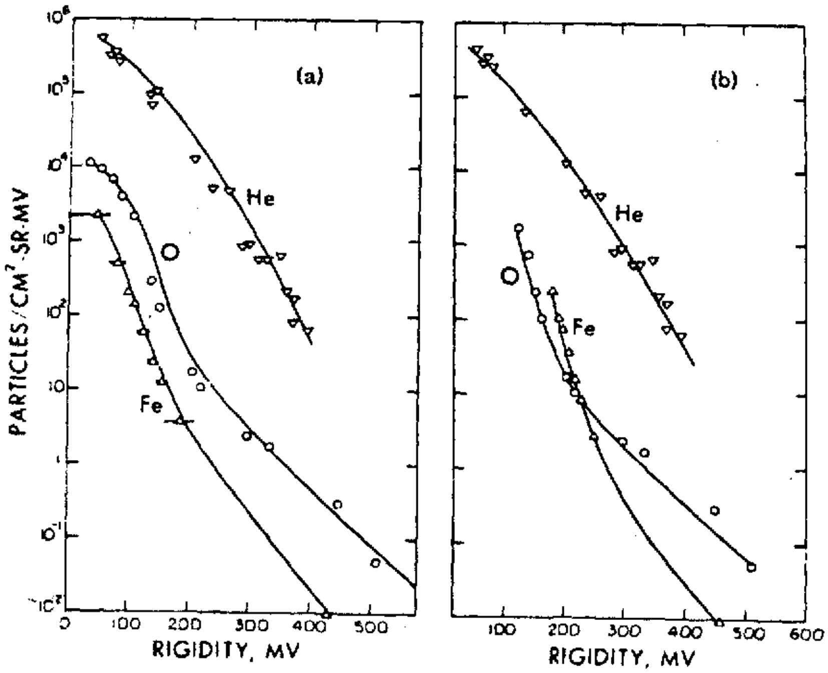

FIG. 3. Rigidity spectra for He, O, and Fe ions, computed (a) assuming fully stripped nuclei, and (b) assuming ions in charge equilibrium given by Eq. (1).

with βc the velocity and m_p the mass of a nucleon; and (b) assuming the ions had passed through enough matter to be in charge equilibrium, with Ze replaced by the effective charge Z^*e, using the semiempirical expression[11]

$$Z^* = Z[1 - 1.032\exp(-137\beta/Z^{0.69})]. \qquad (1)$$

The shapes of the rigidity spectra computed in Fig. 3 depend strongly on the charge/mass ratios of the ions. The glass and Lexan detectors measure ionization rate and range, both of which are independent of the incident-ion's initial charge state, which will approach an equilibrium value given by (1) as soon as it has penetrated a few hundred angstroms of detector thickness. Though we cannot offer a convincing proof, it seems to us far more likely that the acceleration mechanism leads to rigidity spectra that are nearly parallel, as in Fig. 2(a), rather than to rigidity spectra that intersect and signify enormous heavy-ion enhancements at low rigidity, as in Fig. 2(b).

We therefore suggest that the ions were completely stripped of their electrons while being accelerated, at least in the final stage during which their rigidity spectra were being established. A suitable stripping mechanism would appear to be impact ionization by multi-keV electrons, whose presence in the flash phase of a flare is inferred from x-ray observations.

None of the existing models for preferential acceleration of heavy ions[1,12-15] can account for the strongly increasing abundance of heavy ions with decreasing energy, subject to the constraint that the ions were probably completely stripped while being accelerated. Perhaps we should consider differences in the behavior of light and heavy nuclei that do not depend on their charge/mass ratio. Two examples of such a difference are a Maxwellian distribution for which the most probable velocity scales as $A^{-1/2}$, and nuclear Coulomb scattering in a gas, for which the cross section has a complicated dependence on Z and A. The latter may be attractive in view of the recent evidence from He isotope studies[16] that flare particles may pass through several grams per square centimeter of gas while being accelerated.

We have had useful conversations with R. Cowsik, R. Gordon, J. A. Simpson, and J. D. Sullivan. We are grateful to J. Steel for her assistance in all phases of the experiment. We thank L. J. Lanzerotti and M. van Hollebeke for sharing their α-particle data with us.

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[1]P. B. Price, I. D. Hutcheon, R. Cowsik, and D. J. Barber, Phys. Rev. Lett. 26, 916 (1971).

[2]H. J. Crawford, P. B. Price, and J. D. Sullivan, Astrophys. J. 175, L149 (1972).

[3]A. Mogro-Campero and J. A. Simpson, Astrophys. J. 171, L5 (1972), and 177, L37 (1972).

[4]T. P. Armstrong, S. M. Krimigis, D. V. Reames, and C. E. Fichtel, J. Geophys. Res. 77, 3607 (1972).

[5]B. J. Teegarden, T. T. von Rosenvinge, and F. B. McDonald, Goddard Space Flight Center Report No. X-661-72-222, 1972 (to be published).

[6]L. J. Lanzerotti, C. G. Maclennan, and T. E. Graedel, Astrophys. J. 171, L5 (1972).

[7]After this manuscript was prepared, we received a paper by R. L. Fleischer and H. R. Hart, Jr., Phys. Rev. Lett. 30, 31 (1973), reporting heavy-element enrichments during the 17 April 1972 flare. They did not attempt to resolve elements, but simply made range measurements in two track detectors with sensitivity thresholds corresponding to low-energy particles with $Z \gtrsim 6$ and $Z \gtrsim 10$. Their energy spectra were inferred via range-energy relations chosen on the assumption that the tracks in the two detectors were made by ^{16}O and ^{56}Fe ions, respectively.

[8]P. B. Price, D. Braddy, D. O'Sullivan, and J. D. Sullivan, Apollo 16 Preliminary Science Report, NASA Special Publication, 1972 (to be published); R. L. Fleischer and H. R. Hart, *ibid;* D. Burnett, C. Hohenberg, M. Maurette, M. Monnin, R. Walker, and D. Wollum, *ibid.*

[9]R. A. Stern and P. B. Price, Nature (London) 240, 82 (1972).

[10]S. Biswas and C. E. Fichtel, Space Sci. Rev. 4, 709 (1965).

[11]H. D. Betz, Rev. Mod. Phys. 44, 465 (1972).

[12]A. A. Korchak and S. I. Syrovatskii, Dokl. Akad. Nauk SSSR 122, 792 (1958) [Sov. Phys. Dokl. 3, 983 (1958)].

[13]A. V. Gurevich, Zh. Eksp. Teor. Fiz. 38, 1597 (1960) [Sov. Phys. JETP 11, 1150 (1960)].

[14]R. Cowsik, in *Proceedings of the Twelfth International Conference on Cosmic Rays, Hobart, 1971*, edited by A. G. Fenton and K. B. Fenton (University of Tasmania, Australia, 1972), Vol. 1, p. 329.

[15]B. G. Cartwright and A. Mogro-Campero, Astrophys. J. 177, L43 (1972).

[16]J. D. Anglin, W. F. Dietrich, and J. A. Simpson, in "Proceedings of the NASA Conference on High-Energy Phenomena on the Sun," 1972, edited by R. Ramaty (to be published).

15. Cosmic Ray Experiment

INTRODUCTION

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

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

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

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

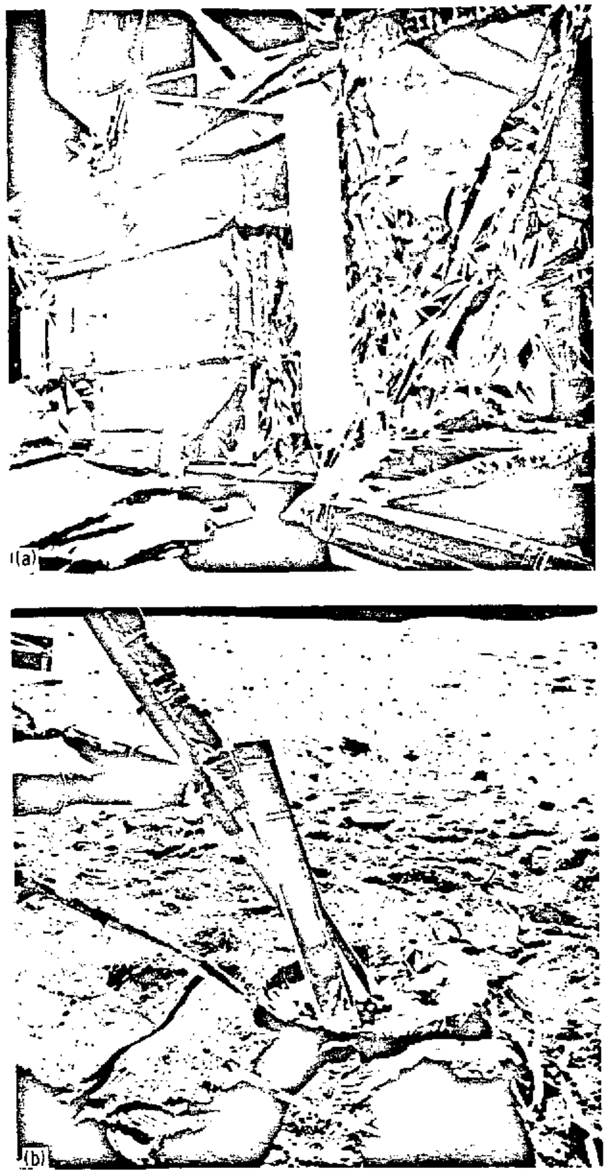

FIGURE 15-1.–The cosmic ray experiment (a) on the descent stage of the lunar module, of Apollo 16, where originally mounted, and (b) on the LM minus Y footpad (on the left footpad, looking down-Sun), where it was placed during EVA 1. Panel 2 and the bottom of panel 3 were used for the GE experiment;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

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

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

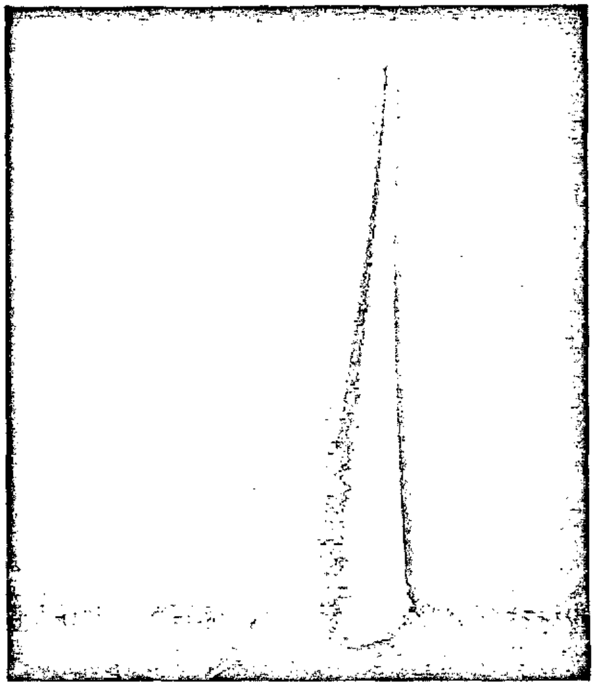

FIGURE 15-2.–Replica of a 0.07-cm etched track in an Apollo space helmet. From the shape, the track can be inferred to have been caused by a zinc ion.

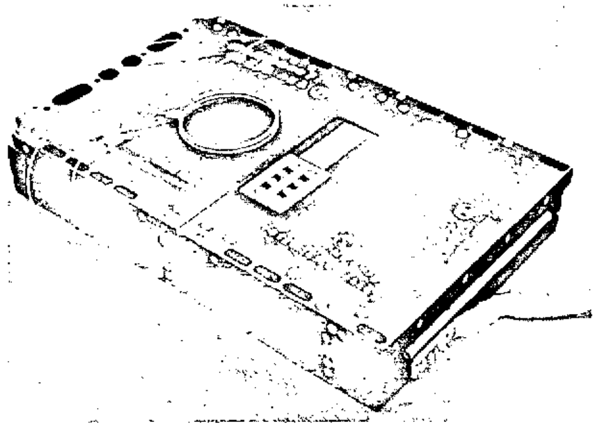

FIGURE 15-3.–Folded detector array. After exposure, the array was folded into the configuration shown to form a convenient package for return to Earth. Temperature labels are visible.

PART B

COMPOSITION OF INTERPLANETARY PARTICLES AT ENERGIES FROM 0.1 TO 150 MEV/NUCLEON

P. B. Price,[a] D. Braddy,[a] D. O'Sullivan,[ab] and J. D. Sullivan[a]

Introduction

The University of California cosmic ray experiment on Apollo 16 was designed to identify tracks of energetic nuclei with atomic numbers $Z \geqslant 2$ in the energy interval from ≈0.2 to ≈150 MeV/nucleon. Improved techniques allowed the energy interval to be extended to ≈0.1 MeV/nucleon. The goal of the experiment was to determine the composition and origin of interplanetary particles in the little-explored energy interval between solar wind energies (≈10^{-3} MeV/nucleon) and energies accessible to balloon-borne instruments (≈300 MeV/nucleon).

Energy spectra determined during solar quiet times by electronic detectors on satellites have been published (refs. 15-22 to 15-24) for iron group nuclei ($25 \leqslant Z \leqslant 28$) down to energies of ≈150 MeV/nucleon; for neon, magnesium, and silicon down to ≈50 MeV/nucleon; for boron and carbon, nitrogen, and oxygen (CNO) down to ≈40 MeV/nucleon; and for isotopes of hydrogen (H) and helium (He) down to ≈10 MeV/nucleon. The presence of boron, which is largely a spallation product of CNO, suggests that medium-charge galactic cosmic rays are present in interplanetary space down to energies of ≈40 MeV/nucleon. The presence of ^{2}H and ^{3}He, which are

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largely spallation products of ^{1}H and ^{4}He, suggests that low-charge galactic cosmic rays are present down to even lower energies (≈10 MeV/nucleon). Nothing has been known before now about the origin (or even the existence) of nuclei at energies less than ≈10 MeV/nucleon present during solar quiet times. For heavy nuclei such as iron, knowledge is limited to greater than ≈150 MeV/nucleon. The limitation has been an experimental one. Electronic detectors on satellites detect only particles with range sufficient to penetrate various windows. Recent improvements in electronic detector design are reducing the minimum accessible energies, but experiment results for quiet times have not yet been published.

At very low energy (≈10^{-3} MeV/nucleon), the Sun continuously emits particles from hydrogen up to at least iron, the solar wind. Light ions of solar origin have occasionally been detected in interplanetary space with suprathermal energies (typically ≈0.01 MeV/nucleon) (ref. 15-25); and tracks of heavy ions ($Z \geqslant 20$) with energies above 0.01 MeV/nucleon have been observed in a glass filter from the Surveyor III camera (refs. 15-26 to 15-28), in an Apollo 12 spacecraft window (ref. 15-28), and in the lunar soils and rocks (refs. 15-29 and 15-30). In all these cases, it is most likely that the ions originated in solar flares.

The Solar Flare of April 18, 1972

A solar particle event occurred on April 18, 1972 (the second day of the Apollo 16 mission). It is not known what activity at the Sun was responsible, but the probable activity was just beyond the west limb, associated with a small X-ray burst and prominence activity about 1800 Greenwich mean time on April 17. The solar particle event had an extremely steep energy spectrum. The proton counting rates are given in figure 15-12. The energy spectrum was so steep that it was possible to study the composition of solar particles and, at the same time, to study preexisting interplanetary particles although not at as low an energy as originally hoped. Previously, the composition of solar particles emitted in only the most intense flares that occur occasionally during an 11-yr cycle had been studied. Rockets, which remain aloft for only approximately 4 min, are reserved for those rare flares of sufficient intensity to provide results of statistical significance. At energies of a few million electron volts per nucleon, flare particles have recently been found to be enriched in heavy nuclei such as iron (refs. 15-28, 15-31, and 15-32). The Apollo 16 experiment made it possible to test whether the composition depends on the strength of the flare as well as on energy.

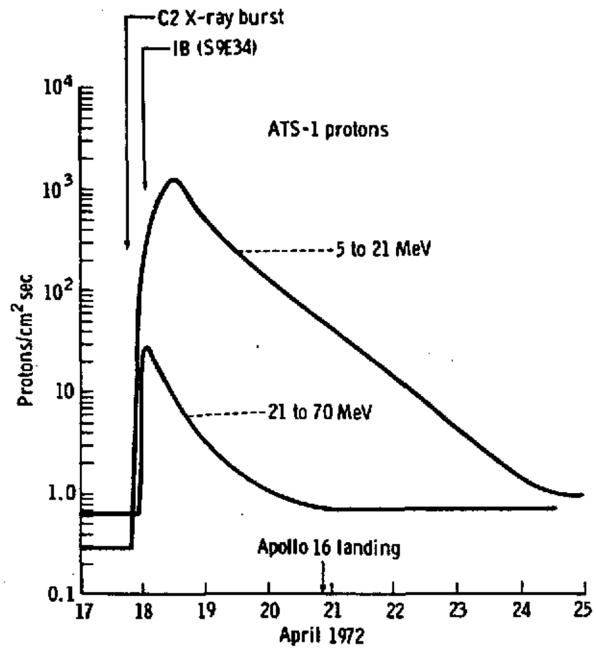

FIGURE 15-12.–Counting rates for protons in two different energy intervals determined on the Applied Technology Satellite (ATS).

Identification of Charged Particles

Dielectric track detectors have the following significant advantages over electronic detectors.

(1) Dielectric track detectors are not restricted in counting rate and can record solar flare particle tracks or galactic particle tracks with equal efficiency. Therefore, the problem of having the most abundant nuclei (hydrogen and helium) monopolize the data storage system does not arise.

(2) With ingenuity, dielectric track detectors can be used to energies much less than 1 MeV/nucleon. No inert window is needed, and the minimum range necessary for an acceptable signal may be as little as 1 μm in special cases.

(3) Dielectric track detectors can be made in virtually any size.

(4) A dielectric track detector can be used with a threshold that discriminates against unwanted particles below some minimum ionization rate.

The sensitivity of certain plastic detectors (Lexan, in particular) is increased by an ultraviolet (UV) irradiation. Coating the top sheet with 100 nm of aluminum is sufficient to eliminate that problem.

The chemical reactivity of tracks may decrease at elevated temperatures such as are reached in full sunlight on the lunar surface. The design of the heat shield is discussed in part A of this section.

The techniques for identifying charged particles by etching dielectric solids have been discussed in a comprehensive review (ref. 15-33), which includes

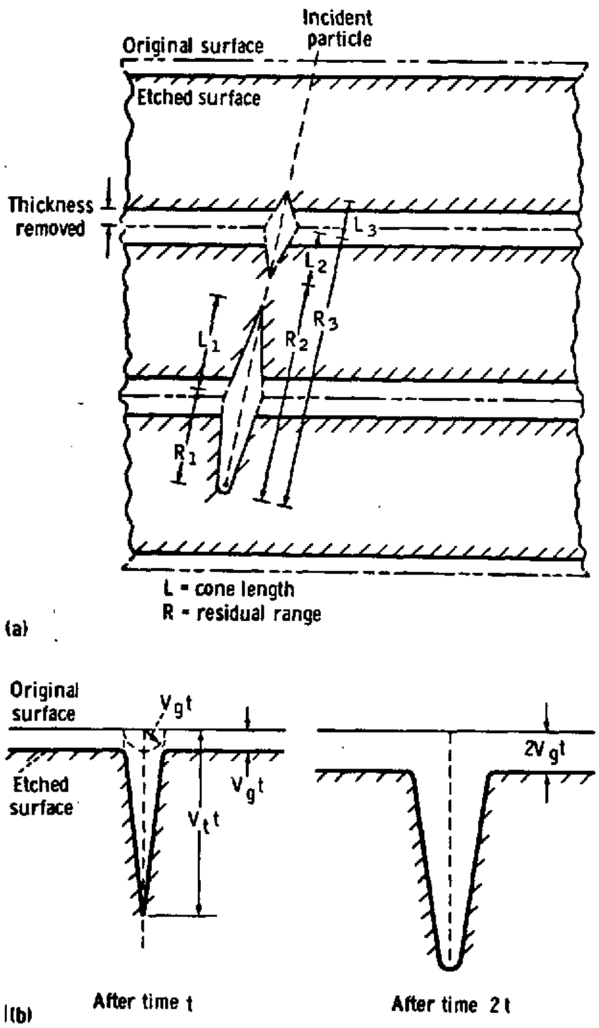

FIGURE 15-13.–Particle identification by etching rate method.

chemical etching reagents for Lexan, cellulose triacetate (CTA), and silica glass. The following paragraphs contain a brief synopsis of the basic technique.

The basic idea (fig. 15-13) is that the rate of dissolution of a dielectric solid in a chemical etching solution is faster along the trajectory of a heavily ionizing particle than elsewhere. The shape of an etched track is roughly conical and is governed by the local ratio of the rate of etching along the track V_t to the general rate of etching V_g, which applies to all surfaces of the solid (including the exposed walls of the track). After the first etch, the length of an etched cone divided by the etching time gives an average value V_t along that part of the trajectory of the particle. If the particle passed completely through one or more sheets of dielectric solid, then several values of V_t will be obtained that fall on a smooth curve of V_t as a function of R, where R is the residual range of the particle at a point halfway along the cone. From appropriate calibrations with heavy ion accelerator beams, together with an ionization equation of the approximate form $J = AZ^{*2}/\beta^2$ and an empirical relationship between J and V_t, it is possible to generate a set of curves showing the response of a detector to slowing ions of differing Z. In this case, A is a constant, Z^* is the effective charge of the ion, and β is the velocity in units of the velocity of light. An example showing an ion that has passed through two plastic sheets and stopped in a third is shown in figure 15-13(a). Only one etching sequence was necessary. In figure 15-13(b), an ion penetrated only part of a detector. To study such low-energy ions, the etching time must be shortened so that the cone can be initially measured; then the detector is re-etched and the final length of the track is measured. The two measurements give V_t and R.

In the case of the etched cones in silica glass, diameter measurements provide additional information that aids in the determination of Z and R even at extremely small ranges.

The University of California experiment consisted of the following four components.

(1) Panel 1 contained 31 sheets of 250-μm Lexan, each 16.5 by 25.4 cm, fastened so that alternate sheets were translated by 2 mm when the astronauts folded the four hinged panels. This feature made possible the rejection of tracks of cosmic rays that passed through the spacecraft on the return trip. The 31 sheets were covered with a sheet of (50 μm) Teflon silvered on the back and with holes 2.5 cm

apart and 0.5 cm in diameter. The holes allowed a fraction of the stack to have a view of space with no covering material. The Teflon sheet was used to minimize absorption of visible sunlight, maximize emission of infrared, and keep the temperature of the underlying sheets below 343° K.

At some time during the mission, panel 1 became covered with a thin, dull, as yet unidentified film. The thermal properties of the film were so impaired that the final temperature exceeded 353° K. This seriously degraded the performance of panel 1, and, at present, an analysis of the panel has not been begun.

(2) One-half of panel 3 was used in the University of California experiment and contained the following detectors.

(a) A stack of sheets of 200-μm CTA, each 16.5 by 11.5 cm, was fastened so that alternate sheets could be translated 2 mm after the last EVA. Actually, the sheets shifted only ≈1 mm, which sometimes made difficult the determination of whether a track occurred before or after the stack was folded and brought into the spacecraft. The perforated Teflon sheet covering the CTA stack worked well; the temperature did not exceed 343° K, as judged by temperature indicating labels. Laboratory annealing experiments showed that tracks of argon and silicon ions in CTA sheets held at 343° K for 24 hr were decreased in V_t by only approximately 10 percent. The techniques illustrated in figure 15-13 were used to analyze tracks of particles with $Z \geqslant 3$ at energies from ≈0.2 to ≈100 MeV/nucleon.

(b) Tabs of Lexan previously irradiated with argon and krypton ions were inserted at three different depths in the CTA stack. After return, the tabs were etched to see if any fading of the tracks had occurred. The etching rate of the argon tracks proved to be the same, within experimental error, as the etching rate of argon tracks in a control piece kept in the laboratory. The krypton tracks etched three times faster than those in a control sample. At present, the only acceptable explanation is that some solar UV leaked into the panel through one of the holes and increased the reactivity of the krypton sample. Fortunately, CTA is extremely insensitive to UV.

(c) One slab of flame-polished silica glass 2.5 by 2.5 cm, aluminized on the bottom, was mounted on the CTA stack and covered with the Teflon heat shield. The center of the silica detector had a view of space through a 0.6-cm-diameter hole in the Teflon. Calibrations with heavy ion beams showed that, to a very good approximation, none of the ions of common elements in the Sun lighter than iron (e.g., silicon) will provide easily visible etched cones in the silica detector. The silica detector is thus extremely useful for determining the energy spectrum of the solar iron nuclei. It is also useful in searching for trans-iron nuclei among solar particles.

(d) A stack of 40 sheets of 6-μm Lexan, each 5 by 5 cm, was mounted on the CTA stack and covered with the Teflon heat shield. Its central portion viewed space through a 0.5-cm-diameter hole. The function of the stack was to determine the energy spectrum of particles of extremely low energy. Each sheet collects tracks of particles coming to rest in a narrow energy interval corresponding to a thickness of 6 μm of plastic. After irradiating each sheet with an intense dose of UV (λ ≈360 nm), alpha particles leave visible etched cones in the last 1 to 5 μm of their range. The 6-μm stack thus serves as a differential alpha particle detector. Heavier ions leave tracks with nearly parallel walls that are distinctly different from the conical alpha particle tracks.

A more detailed general description of the overall design and deployment of the four panels, including the role of the astronauts, is given in part A of this section.

Results

Because of the passive nature of the detectors, it should be emphasized that the measurements and identification of tracks will extend over at least a 12-month period, in contrast to electronic experiments, which may be completed soon after a mission ends. At present, the results are still being analyzed, but the following conclusions have been reached.

Energy spectrum of particles with $Z \geqslant 6$.–The pair of photographs in figure 15-14(a) compares etch pits in a piece of silica glass irradiated with a beam of 3 MeV/nucleon iron ions in the University of California 224-cm cyclotron and etch pits in the uncovered portion of the silica glass irradiated in the solar flare. The density of tracks in the uncovered portion of the silica glass was 5×10^5 tracks/cm^2, which represents stopping iron nuclei alone. Some of the $\approx 3 \times 10^6$ tracks/cm^2 in the CTA (mainly $Z \geqslant 6$) are shown in figure 15-14(b), and some of the $\approx 2.5 \times 10^6$ tracks/cm^2 in the Lexan from panel 1 are shown in figure 15-14(c). At the top of the stack of 6-μm

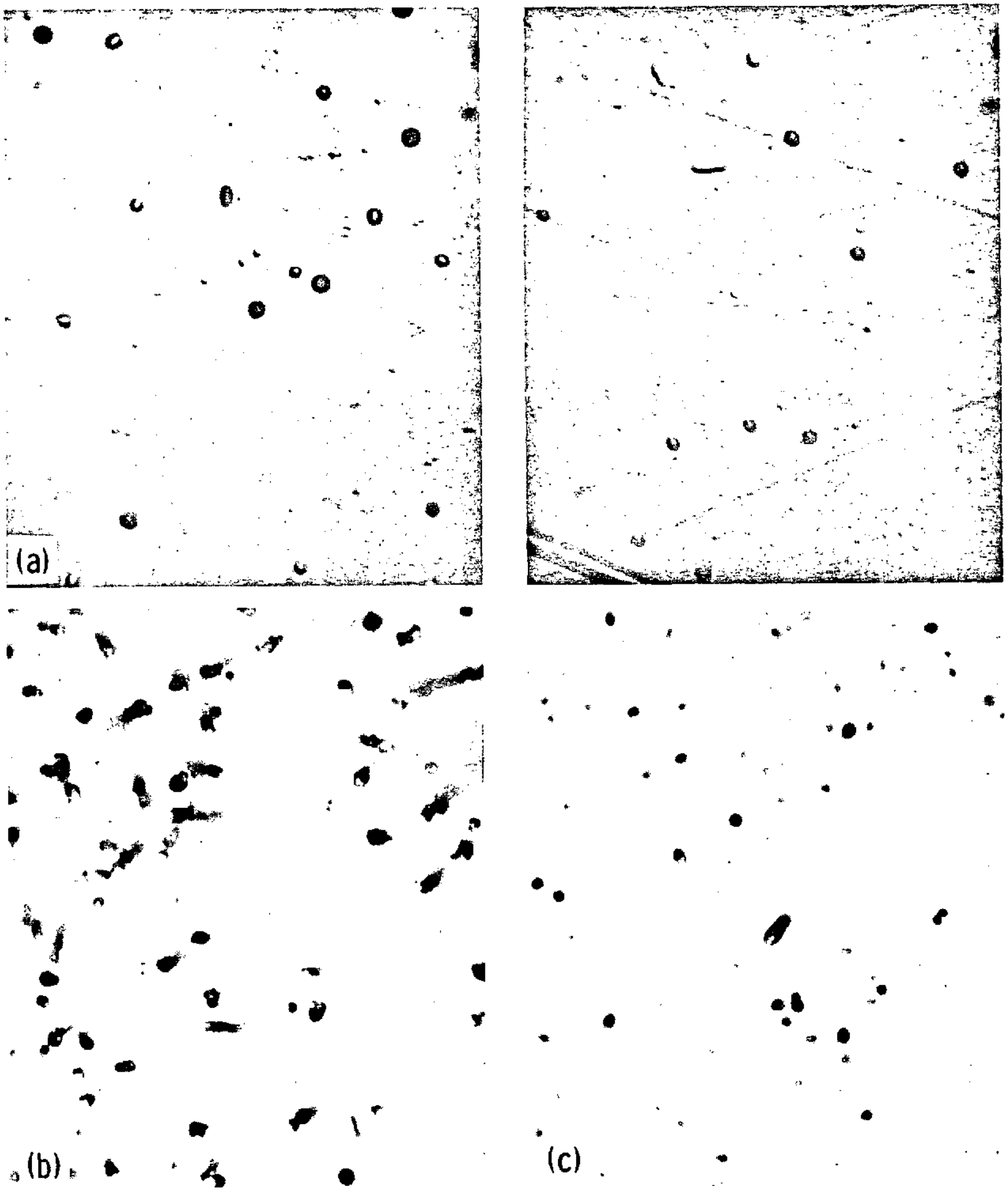

FIGURE 15-14.–Tracks of solar flare particles with $E \approx 0.1$ to ≈ 1 MeV/nucleon. (a) Etch pits of iron nuclei in the silica glass (left) compared with etch pits from iron nuclei produced in an accelerator (right). (b) Etched tracks of nuclei with $Z \geqslant 6$ in CTA from panel 3. (c) Etch pits of nuclei with $Z > 6$ in Lexan from panel 1, which was overheated. Each field of view is 70 by 53 μm.

Lexan sheets, the density of alpha particle tracks was difficult to determine quantitatively amid the background of heavy particle tracks and, at present, only a deeper sheet has been quantitatively studied.

Figure 15-15 shows portions of the energy spectra for four different charge groups: helium, $Z \geqslant 6$ (mainly CNO), $10 \leqslant Z \leqslant 15$, and iron. The helium point at $\approx$2 MeV/nucleon was determined from tracks of alpha particles that stopped in the part of sheet 3 of the thin Lexan stack that was covered with

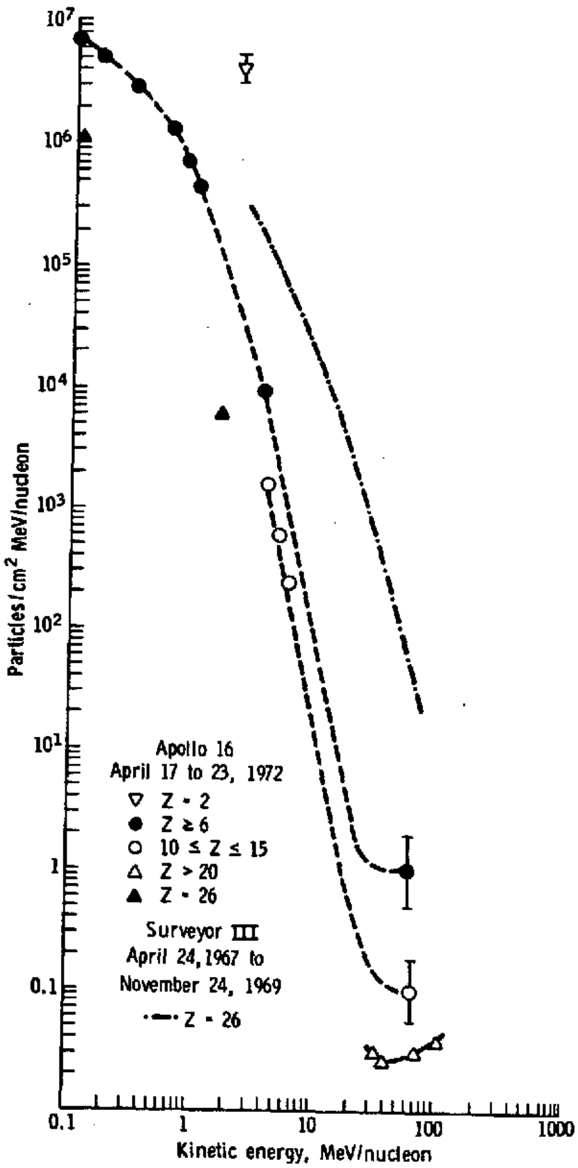

FIGURE 15-15.—Differential energy spectra for various charge groups during the period April 16 to 23, 1972.

50 μm of Teflon. The points for $Z \geqslant 6$ at energies of 0.1 to 1 MeV/nucleon were determined in CTA after a 1-hr etch; the point at 60 MeV/nucleon was obtained from a 30-hr etch. The data for $10 \leqslant Z \leqslant 15$ at low and high energies were obtained from CTA etched for 3 and 30 hr. The low-energy iron point was obtained from measurements in silica glass that was etched 1 hr.

One conclusion is that of a steep decrease of flux (by at least seven orders of magnitude) as the energy increases from $\approx$0.1 to $\approx$30 MeV/nucleon, followed by a flat portion at higher energies. At its steepest point, the spectrum falls off as $\approx E^{-5}$, where E is energy. With electronic detectors, solar flare energy spectra for protons and alpha particles have previously been observed that range from $\approx E^{-2.5}$ to $\approx E^{-4}$.

The steep portion could be ascribed to a solar contribution and the flatter portion to a galactic contribution that would not be significantly different in the absence of a flare. Compositional evidence supports this contention.

Composition of the solar flare particles.—At present, measurements of individual elements have been made in the CTA only at an energy of $\approx$4 MeV/nucleon. The limited data obtained from a part of the CTA etched for a time such that nuclei with $2 \leqslant Z \leqslant 14$ could be studied are summarized in table 15-IV. The absence of the secondary nuclei (lithium, beryllium, and boron) strongly supports the contention that the low-energy particles originated in the Sun.

The helium value in table 15-IV was obtained by comparing the helium flux at 2.1 MeV/nucleon in the

TABLE 15-IV.—Relative Abundances of Solar Particles ($E \approx 4$ MeV/nucleon)

Nuclei	*Observed*	*Solar (Cameron)*
Helium	[a]$\approx$ 3000	2100
Lithium + beryllium + boron	0	$\approx$0
Carbon	11	13.5
Nitrogen	3	2.4
Oxygen	20	24
Neon + magnesium + silicon	4.4	$\approx$3 to $\approx$7
Iron	[b]6	.9

[a]Determined by comparing the helium flux at 2.1 MeV/nucleon in thin Lexan stack with the curve for $Z \geqslant 6$ in figure 15-15.

[b]Determined from the ratio of track densities in silica glass to track densities in CTA.

stack of the Lexan sheets with the flux of $Z \geqslant 6$ interpolated from the appropriate curve in figure 15-15.

The iron-to-($Z \geqslant 6$) ratio was estimated at an energy less than ≈0.5 MeV/nucleon by simply comparing the total track densities in the portions of silica glass and CTA directly under the holes in the Teflon heat shield. From comparisons with the rate of etching of iron tracks in silica bombarded with an iron beam in a cyclotron, it was established that the majority of the tracks in the glass were indeed iron. The result, iron/($Z \geqslant 6$) ≈ 6 for $E < 0.5$ MeV/nucleon, is uncertain by as much as a factor of 2 because of differences in stopping power of glass and plastic and because of uncertain recording efficiency of iron at large zenith angles in silica and of CNO at large zenith angles in CTA. The iron abundance is recorded in table 15-IV.

Until another detector can be flown during a solar quiet time, the composition of the energy spectrum and interplanetary particles in the energy interval ≈0.1 to ≈30 MeV/nucleon cannot be determined.

Composition of the particles with $E > 30$ MeV/nucleon.—A portion of the CTA stack was etched 9 hr, and sheets at four different levels corresponding to mean energies of 34, 40, 75, and 105 MeV/nucleon were scanned for tracks of nuclei with $Z \geqslant 14$. Definite abundance peaks at silicon and iron, together with peaks at carbon and oxygen obtained in the solar particle identifications, established that the resolution was easily better than ±1 charge unit. Tracks of particles that entered the panel from the back constituted approximately one-third of the total. These tracks were not counted.

The presently available data are summarized in table 15-V. The number of events with $Z \geqslant 18$, although extremely limited, appears adequate to support the identification of the majority of these nuclei as galactic rather than solar, simply on the basis of the large fraction of secondary nuclei with $17 \leqslant Z \leqslant 25$.

Discussion

New capabilities.—With the UV sensitization technique and a stack of 6-μm sheets of Lexan, it is possible for the first time to determine accurate differential energy spectra of alpha particles to energies as low as 0.1 MeV/nucleon and as high as ≈6 MeV/nucleon, the upper value being limited only by the stack depth. When the analysis is complete, it will be possible to determine definitively whether the spectrum rolls over at low energy or monotonically decreases with increasing energy. The identification of the alpha particles is reliable because protons are not recorded and because lithium and heavier nuclei leave tracks with markedly smaller cone angles than those of alpha particles.

Laboratory annealing and etching experiments on CTA have shown that alpha particle tracks are not observable after a 1-hr etch. Assuming no lithium, beryllium, and boron in the solar particles, it is then possible to attribute all observable tracks to nuclei with $Z \geqslant 6$. Because all nuclei have comparable range-energy relationships over the limited energy interval ≈0.1 to ≈2 MeV/nucleon, it is necessary only to measure range distributions to compute energy distributions for the charge group $Z \geqslant 6$ in this interval. At higher energies, the tracks are long enough that charges can be identified by the etch/re-etch scheme. One of the major new capabilities in this experiment is the ability to explore the newly accessible interval 0.1 to ≈10 MeV/nucleon.

In this laboratory, studies of the rate of growth of cones with etch time in silica glass have established the feasibility of identifying nuclei heavier than iron. Of the ≈10^5 low-energy solar particles that entered the glass through the hole in the Teflon heat shield,

TABLE 15-V.—Relative Abundances of Heavy Galactic Cosmic Rays

Z	At ≈40 MeV/nucleon	At ≈75 MeV/nucleon	At ≈140 MeV/nucleon
Argon	1	0	2
Calcium	3	3	2
Titanium	1	0	1
Chromium	2	1	0
Iron	3	4	4
Nickel	0	0	1
>30	1	0	0

many are likely to be much heavier than iron. If they have the same composition as the Sun, it should be possible to detect charges to at least $Z = 40$. Several may have already been found that are heavier than iron, but the measurements are still in progress.

Enhancement of heavy nuclei in solar flares.–One of the unexpected results of recent solar flare studies is that at low energies the abundance of heavy elements like iron relative to that of light elements may be enriched by a factor of 10 or more (refs. 15-28, 15-31, and 15-32). At present, it is not clear whether the mechanism is associated with effective charge or ionization potential or some other aspect of atomic physics. It is therefore important to obtain systematic data at various energies and for various flare types. It is particularly important to be able, with the same system, to cover a large charge interval to test the idea of Price et al. (ref. 15-28) of an enhancement that increases with charge. The present system, with a capability of studying particles from helium on up, is ideal.

It is extremely interesting in the present work to find such a large abundance of iron relative to lighter elements at energies of ≈1 MeV/nucleon, as shown in table 15-IV. At energies of tens of million electron volts per nucleon where most of the particles are of galactic origin, no enhancement has been found in this work (fig. 15-15). The relatively high iron flux is thus exclusively associated with the flare particles. As data are accumulated, it will be possible to examine the energy dependence of the enhancement in detail.

Within present statistics, no evidence exists, at energies of ≈2 to 4 MeV/nucleon, for any deviation of the abundances of the elements with $2 \leqslant Z \leqslant 14$ from those expected in the Sun. However, the phosphate glass on Fleischer's panel (part A) shows 1.8×10^6 tracks/cm^2 (private communication) and should record mainly particles with $Z \geqslant 10$; the mica on Walker's panel (part C) shows $\approx 2 \times 10^6$ tracks/cm^2 (private communication) and certainly does not record CNO. These densities are within 50 percent of those in the CTA. All these data together indicate an enhancement of the neon-magnesium-silicon-to-CNO ratio at energies less than 1 MeV/nucleon, which disappears at higher energies.

Comparison of the April 18, 1972, flare spectrum with the Surveyor glass data.–In figure 15-15, the solid curve gives the differential energy spectrum of iron nuclei in interplanetary space integrated over a 2.6-yr interval beginning April 24, 1967 (ref. 15-28). The data were obtained by studying etched tracks as a function of depth in the glass filter within the Surveyor spacecraft camera. Because of the existence of an ≈1-μm coating on the surface and the fact that only those particles at a shallow angle could reach the glass, it was not possible to study energies less than ≈1 MeV/nucleon. If the energy spectrum during that 2.6-yr interval continues to increase steeply with decreasing energy, there would appear to be no inconsistency between it and the present data point at 0.1 MeV/nucleon for a single flare. It should be emphasized that the 1-week interval sampled by the Apollo 16 experiment was atypical in that solar particle events like that on April 18, 1972, are very infrequent.

Comparison of the April 18, 1972, flare spectrum with rocket data on flares.–Lexan detectors on rockets launched from Fort Churchill in Canada have recently been used (ref. 15-34) to study the composition of solar particles in the same energy interval accessible in the present experiment. The energy spectra in the rocket-borne detectors differ in an important way from those in figure 15-15. They go through a maximum at ≈1 to 2 MeV/nucleon and fall to zero at energies less than ≈0.2 MeV/nucleon. The present work shows that a well-defined maximum does not occur in all flares and raises several possible explanations for the maximum (ref. 15-34). Low-energy particles might have been excluded at Fort Churchill by a magnetospheric cutoff or because they had not reached the Earth from the Sun at the times of the rocket flights or even because of energy loss in the atmosphere of the Earth.

Origin of interplanetary charged particles with $E < 30$ MeV/nucleon.–The solar flare interference was an unprecedented opportunity to study a weak solar flare. However, studies of the origin of interplanetary charged particles will depend on future opportunities to use the same detectors to study the quiet-time spectra at energies of 0.1 to 30 MeV/nucleon.

Low-energy galactic cosmic rays.–At an energy of ≈60 MeV/nucleon, the flux of nuclei with $Z \geqslant 6$ shown in figure 15-15 is consistent with the flux at the same energy reported by Comstock et al. (ref. 15-22) during the previous period of minimum solar activity in 1964 and 1965. The level of quiet-time solar activity immediately before the flare of April 16 was only slightly above that in 1964 and 1965, as judged from neutron monitor levels. The flux of nuclei $10 \leqslant Z \leqslant 15$ at ≈65 MeV/nucleon during

Apollo 16 was similar to that reported in 1964 and 1965 at the same energy. No data exist for iron group nuclei at energies comparable to those measured in the present experiment.

The argument that these nuclei originated outside the solar system is based mainly on their composition as reported in table 15-V. At energies greater than 1 MeV/nucleon, the flux of nuclei with $17 \leqslant Z \leqslant 25$ is comparable to the iron flux (ref. 15-35), whereas the abundance of the same elements in the photosphere and in solar flares (ref. 15-34) is less than 15 percent that of iron. It seems inconceivable that these nuclei could actually have originated in the Sun but have passed through the amount of matter necessary to make the observed nuclei with $17 \leqslant Z \leqslant 25$ through nuclear reactions in interplanetary space.

The differential energy spectrum of nuclei with $Z \geqslant 6$ falls by seven orders of magnitude over the interval from 0.1 to 20 MeV/nucleon, then remains almost flat up to ≈100 MeV/nucleon. The two parts correspond to contributions from the Sun and from galactic cosmic rays. Any maximum in the spectrum occurs below the lowest energy studied.

At energies much below ≈4 MeV/nucleon, the abundance of heavy elements is enhanced by a large factor relative to lighter elements. At ≈4 MeV/nucleon, the abundances are similar to those in the Sun. At ≳40 MeV/nucleon, the abundances are similar to those in galactic cosmic rays, characterized by the presence of nuclei produced in spallation reactions in interstellar space.

Conclusions

During the Apollo 16 mission, a solar flare produced an enormous amount of low-energy nuclei, many orders of magnitude greater than the level inferred from studies of tracks in the window of the Apollo 12 spacecraft during a time when the Sun was quiet.

Acknowledgments

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GALACTIC HEAVY COSMIC RAYS WITH 5<E<130 MeV/Nucleon

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With stacks of Lexan and cellulose triacetate exposed outside the lunar modules on Apollo 16 and 17, we have studied the spectra and composition of low-energy particles in interplanetary space. For the period 16 to 23 April 1972 (Apollo 16) we measured the spectra of the elements $6\leq Z\leq 28$ at energies $40\leq E\leq 150$ MeV/nucleon. For the period 11 to 13 December 1972 (Apollo 17) we studied CNO, NeMgSi, and elements with $Z>16$ at energies $5\leq E\leq 40$ MeV/nucleon. Using the abundance of charges $17\leq Z\leq 25$ relative to iron as a tracer, we find that the bulk of the heavy particles in interplanetary space at $E>10$ MeV/nucleon are of galactic rather than solar origin. The relative abundances of the various charge groups are independent of energy from ~2 GeV/nucleon down to ~30 MeV/nucleon.

1. Introduction. With increasing energy the differential flux of nuclei in interplanetary space first steeply decreases, then increases to a broad maximum at a few hundred MeV/nucleon, and then decreases as $\sim W^{-2.6}$, where W is the total energy in MeV/nucleon. Except for the steeply decreasing portion at energies below a few tens of MeV/nucleon, the flux varies with the solar cycle in a way that is reasonably consistent with that expected from theories of solar modulation with adiabatic deceleration included. The time-variation of proton and alpha particle spectra has recently been studied down to ~20 MeV/nucleon (Garcia-Munoz et al., 1973), but information on energy spectra of heavy nuclei has not been available below ~40 MeV/nucleon for CNO, ~50 MeV/nucleon for NeMgSi, and ~150 MeV/nucleon for the Fe-group ($23\leq Z\leq 28$) (Comstock et al., 1969). A major purpose of the Lunar Surface Cosmic Ray Experiments on Apollo 16 and 17 was to determine the composition and energy spectra of heavy nuclei at energies below ~100 MeV/nucleon and from these measurements to establish the relative contribution of (1) solar particles, either as a residue from flares or as a continual quiet-time component, and (2) galactic cosmic rays that enter the solar system in spite of solar modulation. The relative abundance of secondary nuclei such as LiBeB and the elements $17\leq Z\leq 25$ as a function of energy should be directly related to the galactic cosmic ray contribution since they are extremely rare in the sun and in solar flare particles.

On the second day of the Apollo 16 mission (18 April 1972) a weak solar flare produced a temporary background of energetic particles that exceeded the quiet-time flux at energies out to ~30 MeV/nucleon. An analysis of the composition and energy spectra of these solar flare particles has been presented elsewhere (Fleischer and Hart, 1973; Braddy et al., 1973). Here we shall discuss the particles with E>30 MeV/nucleon and show that they are of galactic origin. During the Apollo 17 mission, on 13 Dec. 1973 a weak solar event resulted in an increase in the counting rates of particles with energy less than a few MeV/nucleon (J.A. Simpson, private communication). Paper 364 by Chan et al. (1973) discusses the composition and energy spectra of these low energy particles. The solar event was sufficiently weak that we were able to detect galactic cosmic rays down to energies of ~15 MeV/nucleon.

2. The Apollo 16 Experiment ($E>30$ MeV/nucleon). Large stacks of Lexan and cellulose triacetate (CTA) were exposed on the Lunar Module from 16 to 23 April 1972. Details of the equipment are given elsewhere (Price et al., 1973). We have analyzed tracks of particles with $Z\geq6$ that stopped in the CTA. That stack consisted of 40 sheets each 16.5 cm x 11.5 cm in area and 200μ thick and covered with a 50μ silvered Teflon sheet, the purpose of which was to minimize absorption of visible sunlight and maximize emission of infrared. Color-changing indicators confirmed that the temperature of the CTA stack was successfully kept below 70°C throughout the mission (in contrast to the Lexan stack, which became covered with a lunar dust layer and reached a higher temperature). At such temperatures tracks are relatively resistant to thermal annealing.

Two sections, each 20 cm^2 in area, were cut from the stack and etched at 40°C for 20 and 30 hours respectively, in a solution containing 7 parts by volume of 6.25 N NaOH and 5 parts of 12.5% NaClO. We identified tracks of charged particles by measuring etch pit lengths and residual ranges by the method reviewed by Price and Fleischer (1971). The Fe and Si peaks were easily recognizable in the data and were used to determine the constants a and n in the relation between track-etch rate V_t and ionization rate J:

$$V_t = aJ^n \tag{1}$$

where

$$J = 10^{-4}(Z^{*2}/\beta^2)\ [\ln(\beta^2/(1-\beta^2))-\beta^2+K], \tag{2}$$

K is a constant ≈20 and Z* and β are the effective charge and velocity of the ion. The values a = 0.0143 μ/h and n = 2.36 were used to calculate charges from the etch rate data.

We analyzed tracks of about 360 stopping nuclei within energy intervals ranging from 18 to 110 MeV/nucleon for the CNO group to 50 to 220 MeV/nucleon for the Fe group. Figure 1 shows the overall abundance distribution corrected for scanning efficiency and for the size of the energy interval sampled but not corrected for the systematically increasing mean energy with increasing Z.

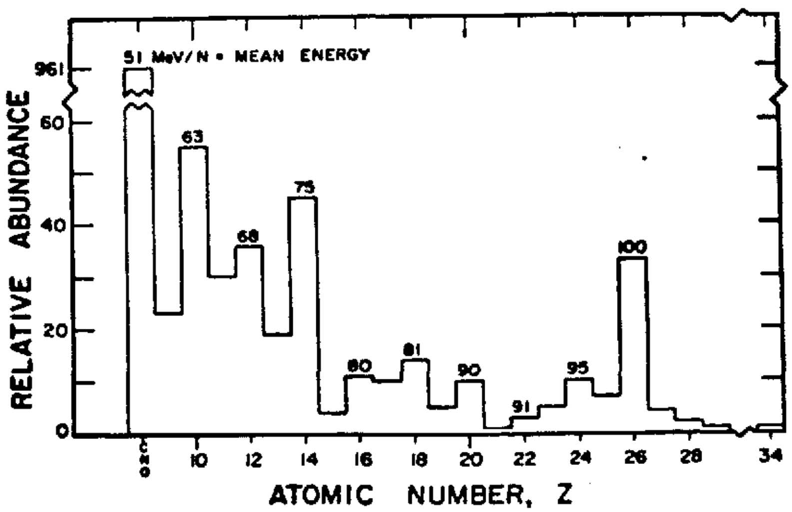

Fig. 1. Relative fluxes per unit energy for nuclei stopping in the stack. The numbers in the graph indicate the mean energies to which the fluxes refer.

Because the fluxes are increasing with energy (Fig. 2), the abundance distribution of Fig. 1 slightly favors heavy elements over light elements but still looks remarkably similar to charge distributions obtained at energies up to a few GeV/nucleon by Cartwright et al. (1971) and Webber et al. (1972). For example, the observed proportion of nuclei with $17 \leq Z \leq 25$ (which are predominantly spallation products) relative to Fe and Ni is 1.51 ± 0.3, which is consistent with values obtained for galactic cosmic rays at E>250 MeV/nucleon (Cartwright et al., 1971; Webber et al., 1972) but is far higher than the value ~0.2 obtained for solar flare particles (Crawford et al., 1972). We can thus make a strong case that the majority of interplanetary particles with E≳30 MeV/nucleon are of galactic rather than solar origin.

In Fig. 2 we have plotted fluxes of the various charge groups in two energy intervals for which the counting statistics are best. The curves in the figure represent the He spectra of Garcia-Munoz et al. (1973), scaled down by a factor 280, in two different years when the Climax neutron monitor rate was nearly the same as during the Apollo 16 mission. The factor 280 is the approximate flux ratio of He to $[23 \leq Z \leq 28]$ observed at energies above ~200 MeV/nucleon. The shape and magnitude of our spectrum for $23 \leq Z \leq 28$ appear to be reasonably consistent with what would be expected if the composition is independent of energy.

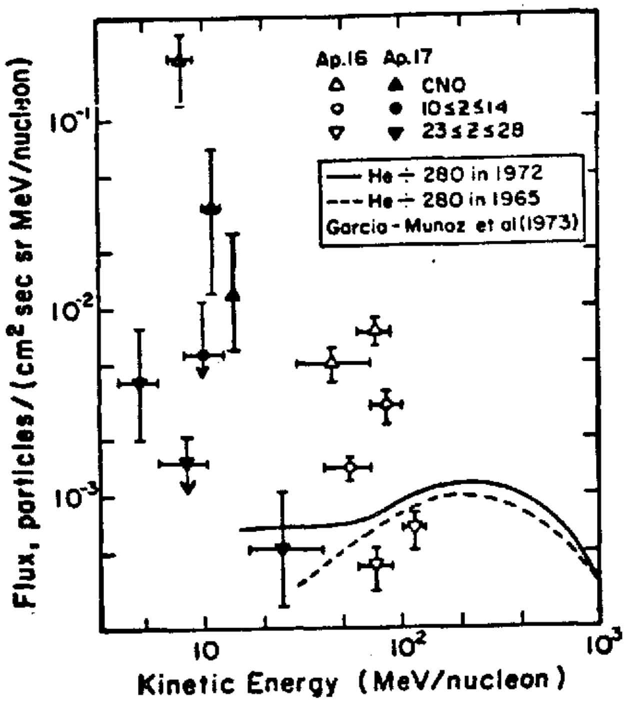

Fig. 2. Energy spectra of low-energy cosmic rays during 16-23 April 1972 (open symbols) when the Climax neutron monitor rate was 4248 and during 11-13 Dec. 1972 (solid symbol) when the rate was 4239.

Stronger evidence that the composition does not change with energy below ~1 GeV/nucleon is given in Table I. Column 2 gives our abundance ratios evaluated in the energy interval shown in column 3, and columns 4 and 5 give the ratios at 250 to 850 MeV/nucleon and at >850 MeV/nucleon determined by Webber et al. (1972). The ratios are independent of energy within counting statistics.

TABLE I. Abundance Ratios

Ratio	Our result	ΔE(MeV/N)	Webber et al. (1972) 250–850 MeV/N	Webber et al. (1972) >850 MeV/N
CNO/(23≤Z≤28)	17.3±5.8	60–90	16.6	17.56
CNO/(FeCoNi)	25.0±8.0	60–90	22.8	21.3
$\frac{10\le Z\le 14}{\text{Fe+Co+Ni}}$	5.6±1.5	60–100	5.76	5.07
$\frac{\text{Ne+Mg+Si}}{\text{Fe+Co+Ni}}$	4.2±1.1	60–100	5.07	4.58
$\frac{17\le Z\le 25}{\text{Fe+Co+Ni}}$	1.50±0.5 1.52±0.6	60–100 100–130	1.15	0.87

3. The Apollo 17 Experiment (5≤E≤40 MeV/nucleon). A stack of 7 sheets of Lexan each 125μ x 3.5 cm x 4.5 cm was exposed for 45 hours in the anti-solar direction, suspended vertically from the Lunar Module while it was on the moon. The top sheet was coated with an ~1000Å layer of Al to screen out ultraviolet light, which would increase the sensitivity to particle tracks in an undesirable way. Unlike the Apollo 16 experiment, this stack was quite small and had no shifting mechanism for rejection events that occurred when the stack was inside the spacecraft. A more detailed description of the experiment is given by Price and Chan (1973).

Half of each sheet in the stack was etched 72 hours in 6.25 N NaOH solution saturated in Lexan etch products. This results in etch pits whose shapes are a measure of the average ionization rates where charged particles impinge on plastic surfaces. After irradiating both sides of each sheet two days with ultraviolet light (Stern and Price, 1972), we re-etched the sheets 5 hours, which succeeds in revealing the remaining portions of particle trajectories. Measurements of etch pits and their extensions permit particles with Z≥5 to be identified and their energies to be determined. Alpha particles can also be identified if they stop within ~10μ of a sheet surface. Though no initial etch pit is visible, the UV and re-etch produce an etched cone of length up to ~6μ that can easily be identified as an alpha track by its distinctive shape. One region of the top sheet was irradiated with ^{16}O ions before the mission to provide a calibration point.

At energies less than ~10 MeV/nucleon, in the portion of the energy spectrum that was steeply falling with energy, the background of unwanted particles was negligible. At higher energies, where the flux was low, a large fraction of the events had to be rejected, either because they entered the detector from the back (possibly passing through the Lunar Module in so doing) while it was on the lunar surface or because they entered the detector when it was inside the spacecraft. We made an estimate of the contribution of unwanted events by determining the fraction that entered the detector from the back and the fraction that entered the detector from the front but apparently from below the horizon. The latter almost certainly occurred not when the detector was hanging on the Lunar Module but when it was lying inside the Command Module.

At this writing we have detected a finite flux of CNO at energies out to ~12 MeV/nucleon but have been able only to set upper limits on the flux of CNO at higher energies. We have set upper limits on the fluxes of the charge groups $10 \leq Z \leq 14$ and $23 \leq Z \leq 28$ at energies from ~5 to ~17 MeV/nucleon. In a scan of the entire etched stack we have found a finite flux of the charges $17 \leq Z \leq 28$ in the energy interval ~17 to 39 MeV/nucleon. In this interval the proportion of charges $17 \leq Z \leq 25$ (which are most likely spallation products of Fe) relative to Fe is comparable to that observed at higher energies and discussed in the previous section. The data are plotted in Fig. 2 as solid symbols.

4. Discussion.

a) Origin of low-energy interplanetary particles. Using the proportion of charges $17 \leq Z \leq 25$ relative to Fe as a tracer of galactic cosmic rays that have entered the solar system after passing through several g/cm^2 of matter, we find that at energies as low as ~15 MeV/nucleon, galactic cosmic rays dominate over solar particles except during periods of solar flares. Using ^2H as a tracer, 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. It thus appears likely that at energies above ~15 or 20 MeV nucleon, the bulk of all the charged particles observed during solar quiet times are galactic cosmic rays. We discuss the origin of the particles of lower energy in paper 364.

b) Energy dependence of cosmic ray composition. In the energy interval between 60 and 130 MeV/nucleon our statistics are adequate to assert that the abundances of the major element groupings - CNO, $10 \leq Z \leq 14$, $17 \leq Z \leq 25$, and FeCoNi - are the same as previously determined at higher energies, up to ~2 GeV/nucleon. The flux ratio of He to the group $23 \leq Z \leq 28$ is less certain because the former was measured with a detector on IMP-5 whereas the latter was measured with our plastic stack on the moon, so that systematic errors in absolute intensity might account for the apparently somewhat higher He/[$23 \leq Z \leq 28$] ratio (≈400) at 60 to 130 MeV/nucleon than at energies of a few hundred MeV/nucleon (≈280). In view of the recent excitement over the discovery that the composition of cosmic rays changes with increasing energy above a few GeV/nucleon (Juliusson et al., 1972; Ormes and Balasubrahmanyan, 1973; Smith et al., 1973; Webber et al., 1973), it is worth emphasizing that the abundance ratios of elements studied with our plastic detectors are reliable and indicate that the composition of galactic cosmic rays with $Z \geq 6$ is independent of energy from ~30 to ~2000 MeV/nucleon.

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References

Braddy, D., Chan, J., and Price, P.B. 1973, Phys. Rev. Letters 30, 669.
Cartwright, B.G., Garcia-Munoz, M., and Simpson, J.A. 1971, in Proc. 12th Inter. Conf. Cosmic Rays, Hobart, Tasmania, 1, 215.
Chan, J.H., Price, P.B., and Shirk, E.K. 1973, These Proceedings, paper 364.
Comstock, G.M., Fan, C.Y., and Simpson, J.A. 1969, Ap. J. 155, 609.
Crawford, H.J., Price, P.B., and Sullivan, J.D. 1972, Ap. J. (Letters) 175, L149.

Fleischer, R.L., and Hart, H.R. Jr. 1973, Phys. Rev. Letters 30, 31.
Garcia-Munoz, M., Mason, G.M., and Simpson, J.A. 1973, Ap. J., in press.
Hsieh, K.C., and Simpson, J.A. 1969, Ap. J. (Letters) 158, L37.
Juliusson, E., Meyer, P., and Müller, D. 1972, Phys. Rev. Letters 29, 445.
Ormes, J.F., and Balasubrahmanyan, V.K. 1973, Nature Phys. Sci. 241, 95.
Price, P.B., and Fleischer, R.L. 1971, Ann. Rev. Nuc. Sci. 21, 295.
Price, P.B., Braddy, D., O'Sullivan, D., and Sullivan, J.D. 1973, Apollo 16 Preliminary Science Report, NASA SP-315, Chap. 15.
Price, P.B., and Chan, J.H. 1973, Apollo 17 Preliminary Science Report, NASA Special Publication, in press.
Smith, L.H., Buffington, A., Smoot, G.F., Alvarez, L.W., and Wahlig, M.A. 1973, Ap. J. 180, 987.
Stern, R.A., and Price, P.B. 1972, Nature Phys. Sci. 240, 82.
Webber, W.R., Damle, S.V., and Kish, J. 1972, Astrophys. Space Sci. 15, 245.
Webber, W.R., Lezniak, J.A., Kish, J.C., and Damle, S.V. 1973, Nature Phys. Sci. 241, 96.