PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Irradiation and Accretion of Solids in Space Based on Observations of Lunar Rocks and Grains

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# Irradiation and accretion of solids in space based on observations of lunar rocks and grains

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[Plate 1]

Clues to a wide range of questions relating to the origin and evolution of the solar system and dynamic physical and electromagnetic processes occurring concurrently and in the past in our galaxy have been provided by a study of the lunar samples. This information is deduced from a variety of complementary physical and chemical evidence. In this presentation, greatest emphasis is laid on information based on the cosmogenic effects, i.e. those arising from interactions of low energy cosmic rays with lunar surface materials. This information is generally not obtainable from examinations of meteorite samples, except in the case of certain types termed gas-rich meteorites, due to loss of their surface regions by atmospheric ablation. The present discussions will concern the nature of experimental data to date and implications thereof to the charged particle environment of the Moon, ancient magnetic fields and the nature of, time scales involved in the irradiation and accretion of solids in space, based on lunar regolith dynamics.

It becomes clear that there does not yet exist any consensus on the absolute values of charged particle or the meteorite fluxes, and also about the details of the evolution of the lunar regolith. This would be expected also considering that one is dealing with phenomena which range in size/energy scales over many orders of magnitude and that the techniques used for the studies were only recently developed in many cases. The complex history of evolution of lunar material is slowly being understood and it is a hope that a great deal of quantitative information will soon be available which will in turn allow discussion of evolution of solid bodies in the solar system.

## 1. Introduction

Our knowledge of interplanetary processes, those occurring in space due to interactions of matter with corspuscular radiation and particles, has steadily grown during the last two decades. The lunar sample acquisition program made positive contribution to space phenomena, but more importantly it highlighted the gaps in our knowledge of the very nature and magnitude of even the simplest processes of the evolutionary history of meteorites, which one had assumed were understood properly. With the development of a variety of nuclear methods for studying the chemical composition of outer surface layers of materials, for the study of solid state and nuclear transformations made by the passage of charged particles, for high resolution examinations of changes induced in the crystalline forms of matter due to incidence of low energy plasma, and high resolution geochronology methods, it is now established beyond doubt that lunar samples are a rich storehouse of information for the scientist interested in the study of dynamic processes occurring in space. Based on this information, one can now begin to construct meaningful models for the evolution, origin and history of meteorites and their parent bodies. Thus, whereas the Moon has not yet disclosed its secrets to the scientists interested in its origin, and the lunar program has not yet led to discovery of any fundamental laws of nature, it certainly has provided a wealth of data on the types of physico-chemical changes which occur when matter is exposed in space for periods of millions of years and the manner in which this interaction has varied in the past.

In this paper we will consider in some restricted manner the types of information emerging about the charged particle environment of the Moon and the manner in which the lunar surface evolved due to nano-, micro-, and macro- meteoritic impacts. It has now been established that a variety of radiation damage effects can be seen in lunar samples, such as formation of amorphous coatings, track formation often at very large areal densities, solar wind sputtering, micro-meteoritic erosion on different scales leading to formation of pits, craters and fragmentation, solid state and isotopic changes due to solar and galactic cosmic radiation, and storage of energy in the form of charge traps (thermoluminiscence) due to solar flare particle irradiation. The literature is vast and some of the recent reviews only will be cited (Crozaz 1975; Horz *et al.* 1975*a*; Maurette & Price 1975; Walker 1975; Gault *et al.* 1974; Hoyt *et al.* 1973; Price *et al.* 1973; Lal 1972). One has now begun to see the great similarity between meteorites and lunar samples and a post-lunar attack towards a closer study of meteorites has proved very profitable (Alfvén & Arrhenius 1975; Anders 1975; Bhattacharya *et al.* 1975; Macdougall *et al.* 1974; Rajan *et al.* 1974; Brownlee & Rajan 1973; Lal 1972).

We will confine our discussions largely to the available information about the present and ancient lunar charged *particle environment* and *lunar regolith dynamics*. Emphasis will be placed on studies based on studies of cosmic ray tracks in which we have been involved. We will also consider the possibility of establishing whether a large scale lunar magnetic field existed at some time in the past.

## 2. Energetic charged particle environment of the Earth in the 1–3 AU space: ancient and present

### (*a*) *The record of charged particles*

Before direct analyses of lunar samples, information on the prehistory of cosmic radiation was obtained from studies of meteorites (Arnold *et al.* 1961; Lal 1969; Kirsten & Schaeffer 1971). This information related primarily to protons of energy $\geqslant$ 500 MeV and $Z \geqslant 20$ (v.h.) and $Z \geqslant 30$ (v.v.h.) nuclei of $\geqslant$ 500 MeV/n kinetic energy. Studies of gas rich meteorites provided information on ancient solar flare radiation (Lal & Rajan 1969; Pellas *et al.* 1969), and of course about the composition of solar wind. The lunar samples provided profuse and diverse information on the low energy radiation environment of the Moon. The principal reason why this record is generally not available in the case of the meteorites is of course the fact that a large surface loss occurs during their atmospheric entry whereby the low energy irradiated samples are lost by mass wastage processes.

The lunar samples are therefore ideally suited for the study of solar flare radiations. The flare accelerated cosmic rays are soft, with most of the radiation being confined to energies much below 100 MeV/n kinetic energy. In lunar samples, one sees a superimposed effect due to the low energy solar flare particles and the harder spectrum due to so-called galactic cosmic radiation. Radiochemical methods allow one to obtain information on the low energy charged particles, protons and $\alpha$ particles. The low threshold radio-isotopes, e.g. $^{22}$Na, $^{26}$Al, $^{53}$Mn, $^{55}$Fe provide information about protons (Shedlovsky *et al.* 1970) whereas the $^{59}$Ni radioactivity in lunar samples which are deficient in nickel, arises primarily from ($\alpha$, $n$) reaction of $^{56}$Fe and provides information on the $\alpha$-particle spectrum (Lanzerotti *et al.* 1973). High threshold isotopes, e.g. $^{36}$Cl, $^{10}$Be and low-threshold isotopes (cited earlier) provide information on higher energy protons. Cosmic ray fossil tracks in common rock minerals are primarily due to the more abundant nuclei of iron group since these minerals efficiently record nuclei of $Z > 20$ (Kratschmaar *et al.* 1973; Price *et al.* 1973; Lal 1972). Etchable tracks form above about 0.3 MeV/n kinetic energy; the total recordable length of iron nuclei can be as large as 100 μm in some minerals. The characteristics of fresh and old tracks are found to be different (Price *et al.* 1973*a*; Dran *et al.* 1973; Kratschmer & Gentner 1975). In 'ancient' samples, the recordable track lengths of iron nuclei in olivines and pyroxenes are found to be in the region of 9–13 μm.

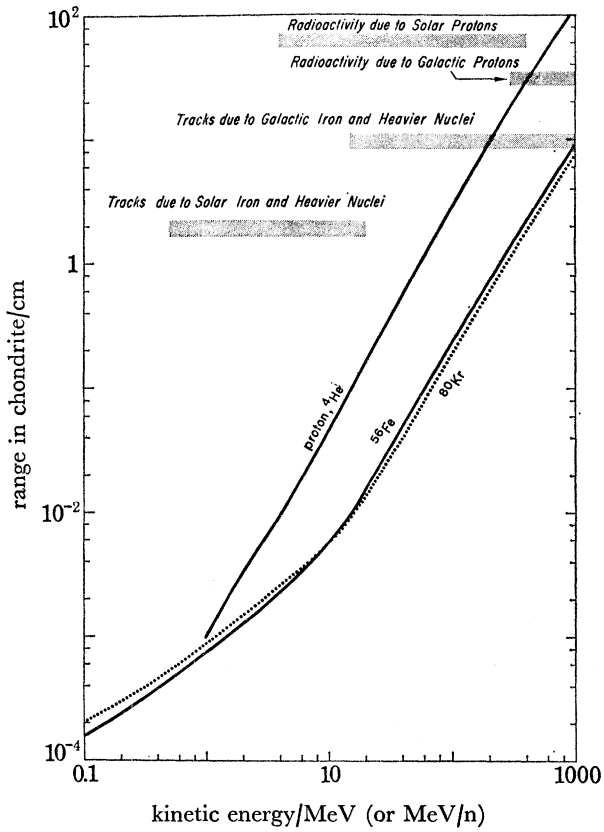



Figure 1. Residual ranges in chondrite, as a function of kinetic energy, for $^{1}$H, $^{4}$He, $^{56}$Fe, and $^{80}$Kr. The approximate energy intervals responsible for the cosmic ray record found in lunar/meteoritic samples are indicated for the solar and galactic cosmic radiation.

With the above information, one can easily delineate the energy regions recorded by the radiochemical and track methods and also the identity of these particles with respect to their source, namely 'solar' or 'galactic'. This is readily seen from figure 1 where the range–energy relation is given for $^{1}$H, $^{4}$He, $^{56}$Fe and $^{80}$Kr. The approximate energy brackets for the solar and galactic tracks/radioactivities are shown by hatched bars in figure 1.

We will now summarize our present day information about the present and ancient energy spectra of the various comsic ray components. For comprehensive reviews on the ancient radiations, reference is made to Lal (1972, 1974) and Price *et al.* (1973*b*). For reviews on the contemporary data reference is made to Meyer *et al.* (1974), Crawford *et al.* (1975), Meyer (1974), Shapiro & Silberberg (1974), Fitchel & McDonald (1967) and Biswas & Fichtel (1965).

As illustrations we give here examples of solar and galactic cosmic ray produced radionuclides and fossil tracks. In table 1, concentrations of the four low-threshold radionuclides, $^{22}$Na, $^{26}$Al, $^{53}$Mn, $^{55}$Fe and two high-threshold radionuclides, $^{10}$Be and $^{56}$Cl are given for Apollo 14 rock 14321 (Wahlen *et al.* 1972); note the large gradients in activities in surface regions of this sample for low-threshold isotopes which are not present in the case of high-threshold nuclides $^{36}$Cl and $^{10}$Be. The excesses in the surface regions are largely due to solar flare proton induced reactions. Similarly, 'excess' solar flare contributions can be seen in the case of soil data

Table 1. Examples of solar flare produced radionuclides in Apollo rocks and soil samples

| | activity disintegrations per min per kg) | | | | | |
|---|---|---|---|---|---|---|
| | $^{55}$Fe (2.5 a) | $^{22}$Na (2.6 a) | $^{26}$Al ($7.4 \times 10^5$ a) | $^{53}$Mn ($3.7 \times 10^6$ a) | $^{36}$Cl ($3.1 \times 10^5$ a) | $^{10}$Be ($2.5 \times 10^6$ a) |
| Rock 14321† | | | | | | |
| 0–0.18 cm | $310 \pm 40$ | $116 \pm 13$ | $148 \pm 16$ | $44 \pm 3$ | $10.7 \pm 1.5$ | $12.8 \pm 2.3$ |
| 0.18–0.47 cm | $135 \pm 20$ | $71 \pm 7$ | $109 \pm 13$ | $36 \pm 2$ | | |
| ~ 6.0 cm | $26 \pm 7$ | $39 \pm 5$ | $57 \pm 7$ | $23 \pm 2$ | $11.2 \pm 1.6$ | $13.8 \pm 20$ |
| ~ 12 cm | $34 \pm 8$ | $32 \pm 4$ | $54 \pm 8$ | $25 \pm 2$ | $12.1 \pm 1.6$ | $12.3 \pm 2.0$ |

| Apollo 15 core‡ code no. | average depth | $^{22}$Na | $^{26}$Al |
|---|---|---|---|
| 15006, 115, 116 | 5.6 cm | $34 \pm 13$ | $60 \pm 8$ |
| 15006, 75–80 | 21 cm | $32 \pm 2$ | $47 \pm 3$ |
| 15006, 50–55 | 32 cm | $34 \pm 8$ | $56 \pm 4$ |
| 15005, 46–51 | 50 cm | $30 \pm 6$ | $46 \pm 3$ |
| 15005, 104–109 | 79 cm | $32 \pm 14$ | $42 \pm 6$ |
| 15004, 73–78 | 95 cm | $14 \pm 11$ | $43 \pm 5$ |
| 15002, 70–75 | 184 cm | $< 17$ | $15 \pm 4$ |
| 15001, 93–96, 98, 99 | 217 cm | $7 \pm 5$ | $14 \pm 2$ |

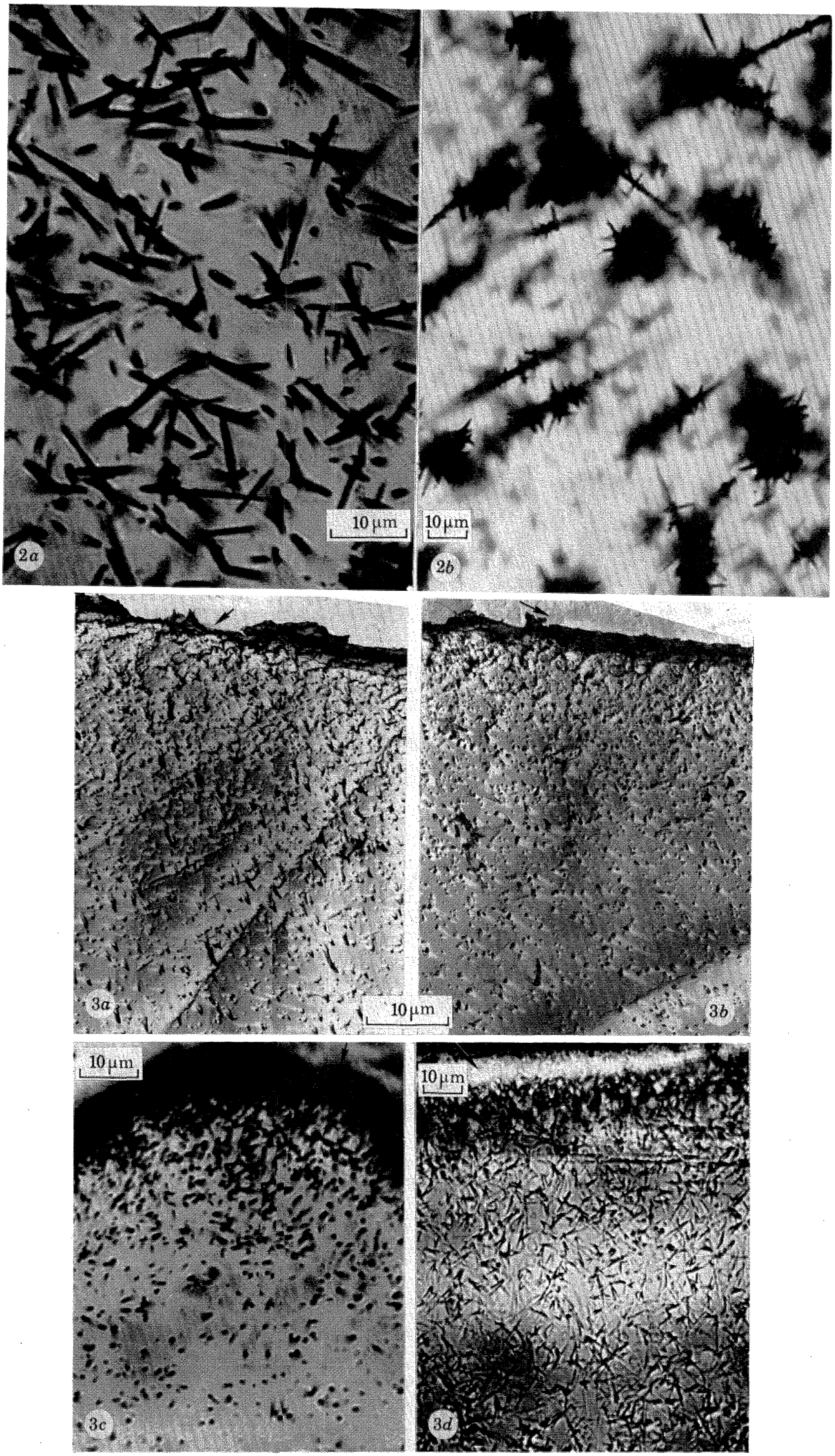
| Apollo 17 trench soil§ at station 3 | $^{22}$Na | $^{26}$Al |
|---|---|---|
| 73221 trench top skim soil | $291 \pm 14$ | $164 \pm 8$ |
| 73241 trench middle | $98 \pm 5$ | $79 \pm 4$ |
| 73261 trench bottom | $38 \pm 4$ | $50 \pm 4$ |
| 73281 trench bottom | $39 \pm 8$ | $39 \pm 4$ |

† Wahlen *et al.* (1972). ‡ Rancitelli *et al.* (1975). § Yokoyama *et al.* (1975).

## Description of plate 1

Figure 2. Photomicrographs of fossil tracks due to cosmic ray nuclei of $Z > 20$ nuclei in mineral grains from the meteorites, Moore County (*a*) and (*b*) Patwar. In the Moore County sample, all tracks etched on a ground surface are shown whereas in the case of Patwar, the surface tracks were removed and only the longer tracks due to v.v.h. nuclei ($Z \geqslant 30$) are visible.

Figure 3. Examples of cosmic ray tracks in lunar and meteorite grains irradiated with low energy iron group and heavier nuclei: (*a*) and (*b*) are lunar olivine grains from samples 76501 and 12028; (*c*) Luna 20 olivine grain; (*d*) Kapoeta feldspar grain. Figures (*a*) and (*b*) are electron micrographs of replica of fossil tracks whereas (*c*) and (*d*) are optical photomicrographs. Evidence for low energy irradiation was first found during analyses of Kapoeta meteorite (Lal & Rajan (1969) and Pellas *et al.* (1969)). Photographs (*c*) and (*d*) are from Bhandari *et al.* (1973*e*) and Wilkening *et al.* (1971). →, edge.




FIGURES 2 AND 3. For description see opposite.

(*Facing p.* 72)



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(Rancitelli *et al.* 1975; Yokoyama *et al.* 1975). In figures 2 and 3, plate 1, we show examples of solar and galactic fossil tracks in meteorites and lunar samples. Both the radionuclide and track technologies have reached a high and sophisticated state of perfection although in the latter case problems still exist in charge calibration and absolute track density ($\rho$) measurements for $\rho \geqslant 10^8\ \mathrm{cm^{-2}}$.

We will now summarize the existing data in the following and then present a broad view critique including comments on data where there exists no consensus.

### (*b*) *Energy spectra of charged particles*

In the case of solar protons, the short and long term averaged fluxes and spectral shapes, as defined by the mean-lives of the radionulcides studied (see table 1: 3.7–($4.5 \times 10^6$) years) correspond to the following differential rigidity ($R$) spectra (Wahlen *et al.* 1972; Lal 1974):

$$\left.\begin{array}{l} \mathrm{d}N/\mathrm{d}R = \text{constant}\ \exp-(R/R_0), \\ \text{With } R_0 = 100\ \text{MV and omnidirectional integrated flux,} \\ J_0, \text{ of } \geqslant 10\ \text{MeV protons} = 100\ \mathrm{cm^{-2}\,s^{-1}}. \end{array}\right\} \quad (1)$$

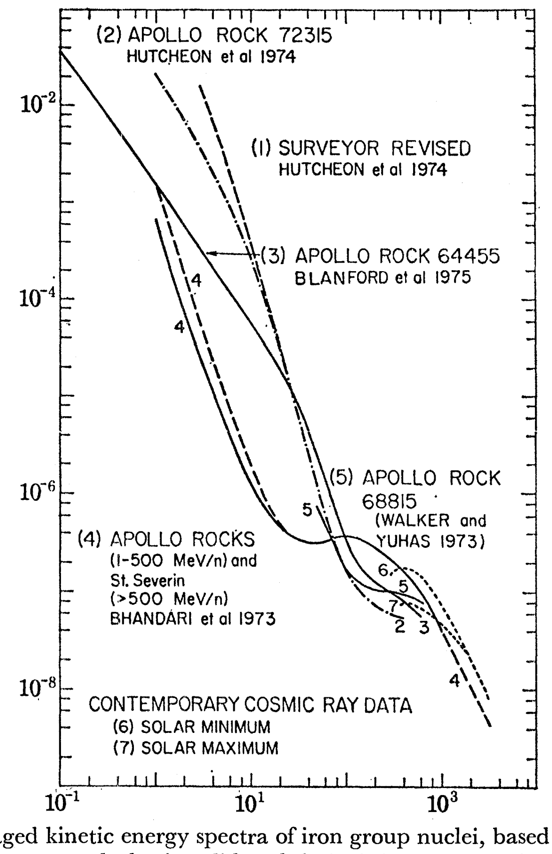


FIGURE 4. Long term averaged kinetic energy spectra of iron group nuclei, based on the study of lunar rocks and meteorites. The two curves marked 4 in solid and dashed lines are based on erosion rates of $2.5 \times 10^{-8}$ and $5 \times 10^{-8}$ cm a$^{-1}$ respectively. Also given are recent fluxes for the iron group nuclei based on studies of tracks in the Surveyor glass (as revised by Hutcheon *et al.* 1974) and in the contemporary galactic cosmic radiation (cf. Cleghorn *et al.* 1971). Recent cosmic ray data by the Chicago and Durham groups are however about 50% lower (Webber, private communication) and would be in better agreement with the long term spectra, curve 4, for energies above 500 MeV/n.

The recent results of Bhandari *et al.* (1975) based on measurements of $^{26}$Al in a lunar rock yield: $R_0$ = 150 MV and $J_0$ ($E \geqslant$ 10 MeV) = (150–180) protons $cm^{-2}\,s^{-1}$, indicating that the time averaged solar spectrum is harder and more intense than the values reported by Arnold and his colleagues.

The data for high energy galactic protons, $E >$ 500 MeV are deduced to be similar to that at pesent (cf. Kohl 1975). More precise measurements for this energy region come as yet from analyses of meteorites. Careful lunar analyses are needed. In the case of $\alpha$ particles, the results of Lanzerotti *et al.* (1973) give a value of 8 $\alpha$-particles $cm^{-2}\,s^{-1}$ of $E \geqslant$ 2.5 MeV/n; the value of $R_0$ is not yet determined.

After $\alpha$ particles, the next group of nuclei studied with the lunar/meteorite samples are the $Z \geqslant 20$ nuclei. The results of the Indian group, based on a large number of rocks from various Apollo missions, are summarized by Bhandari *et al.* (1973*b*) and Lal (1974). Recently energy spectra based on individual rocks have been published by Hutcheon *et al.* (1974), Walker & Yuhas (1973), and Blanford *et al.* (1975). These data which are not mutually consistent are presented in figure 4; the data cover several orders of magnitude in energy, except in the case of Walker & Yuhas (1973). Higher energy data in the case of Bhandari *et al.* (1973*b*) are based on analysis of fossil track data in the meteorite St Severin.

### (*c*) *Chemical composition of heavy nuclei of* $Z \geqslant 20$

Reliable information on the charge composition of ancient solar and galactic radiation is as yet limited to determination of ratios of the abundances of v.v.h./v.h. (i.e. ($Z \geqslant 30$)/($Z \geqslant 20$)) nuclei. Earlier charge assignments for nuclei within the iron group, based on track length measurements (Lal 1969) seem to be applicable, operationally, in pyroxenes as supported by calibration experiments of Price *et al.* (1973*a*). However the work of Krätschmer *et al.* (1973) and Kratschmer & Gentner (1975) throws some doubt on the earlier work (Lal 1969) which showed that high resolution is attainable with the fossil track method and abundance of individual elements in the iron group can be determined; it must be mentioned that the work of Kratschmer *et al.* (1973) and Kratschmer & Gentner (1975) is largely confined to feldspars and augites, whereas the other investigations concern mainly hypersthenes and olivines. Further work is needed to decide on the recordable length method of ascertaining charge distributions within the iron group. The results of Kratschmer & Gentner (1975) indicate a ratio of 0.6–0.7 for (V + Cr + Mn)/Fe for galactic cosmic radiation.

In the case of v.v.h./v.h. nuclei, their relative abundances can be determined fairly reliably because of the particular abundance pattern of these nuclei in the charge region 26–30. After iron, the abundances drop very rapdily and after copper, the most abundant element is zinc (Cu/Zn ratio = 2.3 according to Cameron (1973)) which constitutes about 80 % of the total abundance of elements in the charge group 30–40. The nuclei in this charge group constitute 97 % of total of the abundance of $Z \geqslant 30$ elements. The Indian group has successfully used the recordable length criterion to measure v.v.h./v.h. ratio in solar and galactic radiation for $E \geqslant$ 5.0 MeV/n (Bhandari *et al.* 1973*b*) and also developed a 'track shape' method for identifying v.v.h. tracks for energies below 5 MeV/n (Goswami & Lal 1975). The ratio of v.v.h./v.h. differential fluxes for $E >$ 20 MeV/n is $1.3 \times 10^{-3}$ independant of energy, a value which is in good agreement with the values of $1.2 \times 10^{-3}$ or $1.8 \times 10^{-3}$ for the solar photospheric value (Withbroe 1971) and universal abundance (Cameron 1973). At lower energies, the ratios are higher than in the photophere as shown in figure 5.

The long term averaged results to date are summarized in figure 5. Price *et al.* (1971) have given relative abundances of $Z \geqslant 40$ nuclei in the galactic radiation, based on observations of long tracks in an Apollo rock. The ratios for abundances of $Z \geqslant 40$, $\geqslant 50$, $\geqslant 70$ and $\geqslant 83$ nuclei relative to Fe nuclei are obtained approximately as $5 \times 10^{-5}$, $10^{-5}$, $3 \times 10^{-6}$ and $3 \times 10^{-7}$ respectively.

### (*d*) *A critique of the data on the ancient charged particle environment of Moon and meteorites*

Plentiful data have been obtained on the prehistoric fluxes and spectrum of charged particle radiation in the lunar space. The results provide ample proof that there have been no major changes in the time averaged flux or form of the solar flare radiation over a very broad interval of energy: for $Z \geqslant 20$ in the $10^{-1}$–$10^{2}$ MeV/n kinetic energy interval and for protons in the interval $10^{1}$ and $10^{2}$ MeV during the last few million years.

In the case of solar protons, the deduced time averaged flux (cf. Wahlen *et al.* 1972) is shown in figure 6 as a function of energy, along with the contemporary data for 'galactic' protons. Time averaged solar proton flux drops rapidly below the galactic intensity for $E > 300$ MeV. In the case of solar v.h. nuclei, the present form of energy spectrum is still undecided, particularly for energies below 100 MeV/n, as discussed earlier.

In spite of uncertainties in the absolute flux of v.h. nuclei, reliable data on the relative abundances of $Z \geqslant 30/Z \geqslant 20$ nuclei in the low energy interval ($< 30$ MeV/n) are available for the past few million years from analyses of lunar rocks and grains (Bhandari *et al.* 1973*f*) and for the time period extending back to a few billion years on the basis of analyses of lunar breccias and gas rich meteorites (Lal & Rajan 1969; Pellas *et al.* 1969; Bhandrai & Padia 1974).

Data on the higher energy radiation for protons and $Z \geqslant 20$ nuclei extending to the thousand MeV region, and for longer time periods of time are as yet based on meteorites (cf. Lal 1974) which were presumbly irradiated at distances of the order of 2–3 AU; the possibility that certain meteorites were irradiated at distances, 5–10 AU cannot be excluded as considered by Anders (1975); see also Price *et al.* (1975).

There is a growing evidence that solar wind flux was higher in the past; the details of this variation are however not known (Geiss 1973). Similarly, some evidence has recently been presented that the ratio of solar flare and solar wind particles was higher approx. 3–4 Ga ago when most of the gas rich meteorites presumably received the part of the cosmic ray irradiation that occurred prior to their compaction (Bhattacharya *et al.* 1975). However, if the solar flare induced track densities are higher in lunar samples than in meteorites, as the present author believes on the basis of some of his unpublished data, the safest conclusion that can be drawn today would be an essential constancy in the relative flux of solar flare energetic particles and solar wind during the past 3–4 Ga.

It may be mentioned that Poupeau *et al.* (1973) concluded that solar activity was higher during the early history of the Moon; this conclusion has however been questioned by Crozaz *et al.* (1974).

It seems fairly well established now that the composition of heavy nuclei remains the same for nuclei of kinetic energies above 20 MeV/n. However in the case of solar nuclei of energies below 10 MeV/n, the abundance of an element relative to a lighter one increases as one goes to lower energies. The evidence for energy dependence in the charge composition for low energy nuclei was presented for the contemporary radiation by Price *et al.* (1971); subsequent experiments using plastic/glass and electronics detector systems have confirmed this interesting observation for many of the recently studied solar flares for elements of atomic number 2–50 (Crawford *et al.* 1975). An inverse energy dependence in the charge composition was also found for the time averaged ancient fluxes of the closely situated charge groups, v.v.h. ($Z \geqslant 30$) and v.h. ($Z \geqslant 20$) nuclei by Bhandari *et al.* (1973*b*), thus confirming that preferential acceleration of heavier nuclei over the lighter one is a characteristic of solar flare acceleration for the 5–10 MeV/n region; the enhancements are largest at 5 MeV/n.

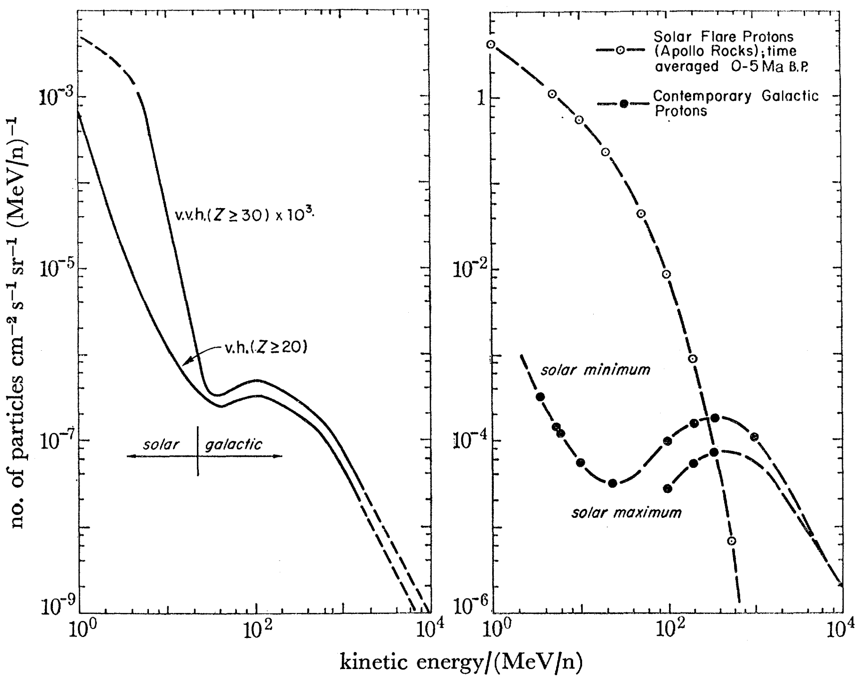


FIGURE 5 FIGURE 6

FIGURE 5. Long term averaged differential kinetic energy spectra for v.h. and v.v.h. nuclei are shown for both the solar and galactic radiations (data from Bhandari *et al.* 1973*a*, *b* and Goswami & Lal 1975).

FIGURE 6. Long term averaged solar proton spectra based on studies of lunar rocks (Wahlen *et al.* 1972) are shown along with the galactic cosmic ray proton data observed during solar maximum and minimum periods.

The observed abundance enhancements for solar cosmic ray nuclei over photospheric abundances obviously could not be expected to persist to the lowest energies, from material balance point of view. It is therefore gratifying to see that the recent extension of data on v.v.h./v.h. abundances to ~ 1 MeV/n by Goswami & Lal (1975) shows that the $(\mathrm{d}N/\mathrm{d}E))_{\mathrm{v.v.h.}}/(\mathrm{d}N/\mathrm{d}E)_{\mathrm{v.h.}}$ ratio begins to decrease at energies below 5 MeV/n and continues to drop till 1 MeV/n (figure 5). Goswami & Lal (1975) have discussed that the observed behaviour in the relative abundances of v.v.h./v.h. with energy, the ratio being highest at *ca.* 5 MeV/n and decreasing at both higher and lower energies (figure 5), probably implies that solar flare particles of different kinetic energies represent samples from different regions of the solar atmosphere; the lowest energy particles studied ($\lesssim$ 1 MeV/n) deriving from the outer chromospheric regions (or near the base of the corona) and higher energy particles being accelerated from deeper regions in the chromosphere, closer to the photosphere.

Turning to the question of long term average fluxes of v.h. nuclei in the 0.1–100 MeV/n energy interval, we have noted earlier that at present there is no consensus between the four groups presenting these results. Differences are quite large to be important both for cosmic ray and lunar physics (see figure 4). Clearly some flux values are too large and others too small, but no scientific justification exists for adopting anyone of these or between the present divergent data.

In figure 7 we present the calculated track production rates in the Moon, as a function of depth for the various spectra, excluding the spectrum of Blanford *et al.* (1975) which represents an intermediate case. Clearly the differences are large, particularly for depths smaller than $10^{-1}$ cm, the erosion controlled region. For applications to regolith dynamics, one would have to standardize track counting methods for the 10–100 μm region and also obtain an operational track production profile for this region.

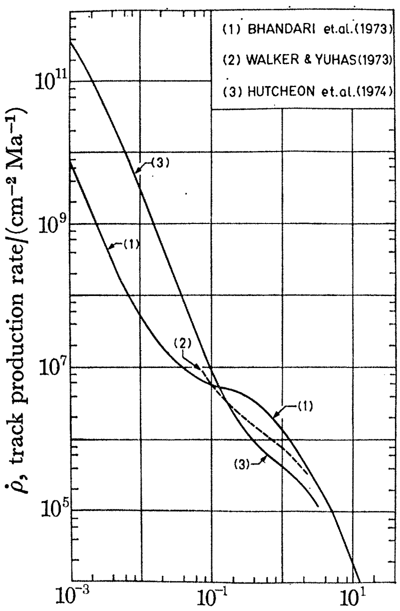


FIGURE 7

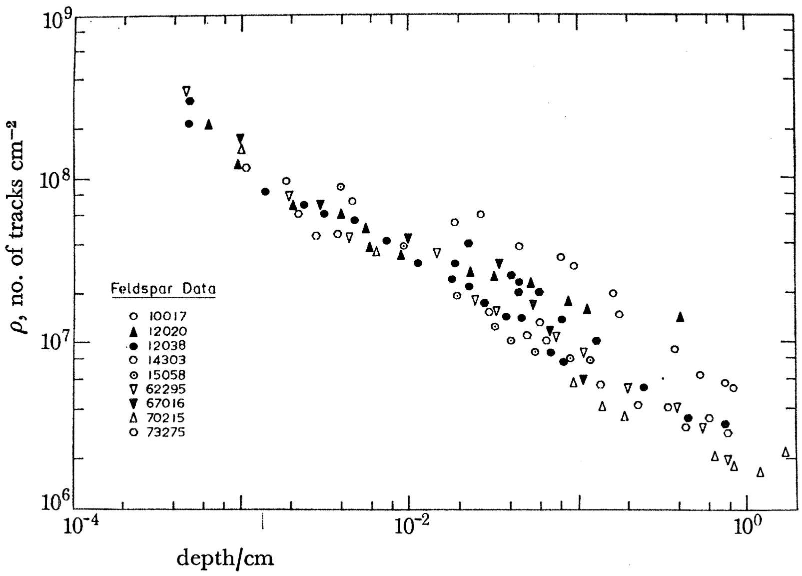


FIGURE 8

FIGURE 7. Calculated track production rates in the Moon for three of the iron group nuclei spectra shown. The spectra labelled (1) corresponds to v.h. flux calculated for a mean erosion rate of $5 \times 10^{-2}$ cm/Ma. All calculations are for $\epsilon = 0$ and a recordable range of 10 μm.

FIGURE 8. Measured track densities in lunar rocks in the mineral feldspar. These data yield values of 2–$5 \times 10^{-2}$ cm/Ma on the Moon (Bhandari *et al.* 1972).

The deviation between the various investigations are certainly due to differences in approach and can largely be attributed to a lack of our understanding of several important parameters which enter the calculations of ($dN/dE$) from the observed track densities. It should be noted that whenever intercomparisons are made on data relating to identical experimental methodology, the agreement is fairly good (Yuhas *et al.* 1972). Presently, part of the differences arise because the procedures for track counting in the high track density regions ($\rho > 10^8$ cm$^{-2}$) are not yet standardized. Optical data relate to tracks of length > 1 μm and for high resolution s.e.m. or electron micrograph replicas, track counts can considerably differ depending on the time of etching. Since it is required to etch different track density regions for different times, it becomes necessary to use sliding correction factors over track density intervals of the order


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of 1 magnitude or thereabouts (Blanford *et al.* 1975). Even as one makes a transition from one technology to the other, for example, from optical to electron microscope, one encounters fairly large differences in track densities, the latter data being higher (cf. Bhandari *et al.* 1971; Crozaz *et al.* 1971; Price *et al.* 1971). Besides, part of the differences arise from the basic approach used by different investigators. The Indian group has studied a large number of rocks and considered the steepest track data for energy spectrum calculations, confining to optical data largely. These rocks have been established to be in erosion equilibrium up to depths of $\sim 10^{-2}$ cm (figure 8). At depths $> 2\times10^{-2}$ cm the track densities diverge for different rocks indicating the non-equilibrium region. The small differences in the observed track densities for depths of between $5\times10^{-4}$ and $10^{-2}$ cm is expected to arise, theoretically, from the orientation angle of the rock surface sampled. Blanford *et al.* (1975) and Hutcheon *et al.* (1974), on the other hand, have each separately based their work on studies of a single erosion unaffected (or least affected) rock. Walker & Yuhas (1973) work primarily in the higher energy region and chose a rock ejected recently from the South Ray Crater; their spectrum for the lower energy side ($<$ 100 MeV/n) are based on the Surveyor data (figure 4) which refers to measurements in one of the Surveyor lenses of the time integrated flux of solar iron group nuclei over a period of 2.6 years (24 April 1967–24 November 1969). The absolute fluxes in each case are obtained by normalization to some spectra either at low (Surveyeor data) or high energies (present cosmic ray or the Walker & Yuhas (1973) or the St Severin flux at higher energies).

Table 2. Long-term integrated v.h. nuclei and proton fluxes (0.1 MeV/n–500 MeV/n)

| nuclei/author | integral flux† in the kinetic energy (MeV/n) interval | | | |
|---|---|---|---|---|
| | 0.1–1.0 | 1–10 | 10–500 | 1–500 |
| (i) v.h. ($Z \geqslant 20$) | | | | |
| Bhandari *et al.* (1973) | — | $3.7\times10^{-4}$ | $1.2\times10^{-4}$ | $4.9\times10^{-4}$ |
| Hutcheon *et al.* (1974) | — | $2.5\times10^{-2}$ | $1.5\times10^{-3}$ | $2.7\times10^{-2}$ |
| Blandford *et al.* (1975) | $6.0\times10^{-3}$ | $2.4\times10^{-3}$ | $6.5\times10^{-4}$ | $3\times10^{-3}$ |
| (ii) solar protons‡ | | | | |
| Wahlen *et al.* (1972) (based on rounded figures of $R_0$ = 100 MV and $J_0 \geqslant$ 10 MeV = 100 cm$^{-2}$ s$^{-1}$) | 7.0 | 12.3 | 7.95 | 20.3 |
| (iii) ratio of v.h./proton§ | | | | |
| Bhandari *et al.* (1973) | — | $3\times10^{-5}$ | $1.5\times10^{-5}$ | $2.4\times10^{-5}$ |
| Hutcheon *et al.* (1974) | — | $2\times10^{-3}$ | $1.9\times10^{-4}$ | $1.3\times10^{-3}$ |
| Blandford *et al.* (1975) | $8.8\times10^{-4}$ | $2\times10^{-4}$ | $8.2\times10^{-5}$ | $1.5\times10^{-4}$ |

† In units of cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

‡ The recent determination of Bhattacharya & Bhandari (1975) are at variance with the deductions of Wahlen *et al.* (1972); they correspond to $R_0$ = 150 MV and $J_0$ ($\geqslant$ 10 MeV) = 150–180 cm$^{-2}$ s$^{-1}$.

§ The v.h./proton ratios in the solar photosphere and in universal abundances are $2.58\times10^{-5}$ and $2.68\times10^{-5}$, respectively (Withbroe 1971; Cameron 1973).

We will now consider the implications of the deduced long term solar and galactic cosmic ray spectra, particularly for the $<$ 100 MeV/n region, where discrepancies are the largest at present. In table 2 we have presented the time averaged fluxes of v.h. nuclei and protons in the 0.1–500 MeV/n region. Considering data presented in figure 4 and table 2, we note the following:

(i) The v.h. spectrum of Bhandari *et al.* (1973) shows that if a detector is exposed for long periods of time in space, (10–15) MeV/n is the central energy above and below which the galactic and solar flare radiations respectively dominate. The data of Blanford *et al.* (1975) and Hutcheon *et al.* (1974) on the other hand show that solar contributions dominate up to 100 MeV/n, or even at few hundred MeV/n energies.

(ii) The enhancement in the v.h. flux over that of protons in the solar flare compared to solar/universal abundances, continued to exist up to or at > 100 MeV/n in the case of data of Blanford *et al.* (1975) and Hutcheon *et al.* (1974). Enhancements are considerable at all energies. In contrast the spectrum of Bhandari *et al.* (1973) shows that at ⩾ (10–20 MeV), the v.h./proton abundances as well as v.h./v.v.h. abundances level off to constant values which agree with the universal abundances (table 2).

(iii) We have compared the various published long term v.h. spectra on the rigidity scale since the rigidity spectra for singly and multiply charged particles for contemporary solar flares have been observed to follow a single spectrum over a wide range of rigidities corresponding to the range of kinetic energies of interest here (Freir & Webber 1963).

If one deduces the exponential rigidity characteristic slope $R_0$, one finds very large values of $R_0$ at energies exceeding 1 and 20–50 MeV/n respectively for the case of Blanford *et al.* (1975) and Hutcheon *et al.* (1974). The calculated values based on the $R_0$–$\gamma$ translation equations given by Lal (1972) are shown in figure 9 for the various published spectra. Firstly such large values of $R_0$ have not yet been observed for multiply charged nuclei in contemporary solar flares (Fichtel & MacDonald 1967; Biswas & Fichtel 1965; see also Lal 1972 for discussion of solar data). The highest $R_0$ value reported so far is 135 MV; typical values of $R_0$ for He and medium nuclei of $E > 40$ MeV/n lie around 100 MV (Biswas & Fichtel 1964, 1965). Secondly, one observes in the case of Blanford *et al.* (1975) and Hutcheon *et al.* (1974) that the spectrum hardens progressively as energy (i.e. rigidity) increases. In solar flares, the typical situation observed for different components is best described by figure 7 of Fichtel & MacDonald (1967), the exponent $\gamma$ for the power law differential kinetic energy spectrum increases smoothly as one goes to higher energies so that the value of $R_0$ remains confined within a narrow range. And $R_0$ values are found to be similar for He and M nuclei. If we expect a similar behaviour for the v.h. and v.v.h. nuclei which have similar $(A/Z)$ ratio, one would *not* expect the long term averaged picture to be as that observed in the case of spectra of Blanford *et al.* or Hutcheon *et al.*, unless of course one assumes that the mean galactic cosmic ray spectra itself, in the 20–100 MeV/n interval contributes appreciably to the deduced time averaged fluxes. The latter assumption will be contradictory to all known facts today on the basis of observation of v.h. nuclei over a whole solar cycle (cf. Meyer *et al.* 1974).

The spectral form of long term averaged solar v.h. nuclei thus differs appreciably from that observed during solar cycles 19 and 20, if the data of Blanford *et al.* (1975) and Hutcheon *et al.* (1974) are accepted as being approximately valid. The deduced spectra of Bhandari *et al.*, for both v.h. and v.v.h. nuclei (figures 4 and 9) and table 2 are however not necessarily in conflict with the recent flare observations. At low energies $E < 10$ MeV/n, the helium spectra are found to have a slope of $-3$ for the kinetic energy power law differential spectrum (cf. Hsieh & Simpson 1970). The v.v.h./v.h. ratios above 20–30 MeV (Bhandari *et al.* 1971*f*) correspond to the universal abundances (Cameron 1973), being $\simeq 1.3 \times 10^{-3}$ (figure 5).

It seems now very important to resolve differences between different investigators and to determine unambiguously the long term averaged spectra and charge composition of $Z \geqslant 20$ nuclei above $E \gtrsim 0.1$–$0.5$ MeV/n. These data clearly have implications to temporal variations in the solar activity, to solar flare acceleration and to galactic cosmic ray propagation characteristics. Turning our attention to the galactic radiation, it may be noted that large compositional differences would probably not be surprising as the solar system would be expected to preferentially receive local particles accelerated from discrete sources situated in different parts of the galaxy, during its orbital motion (Lal 1974; Bhandari & Padia 1973).

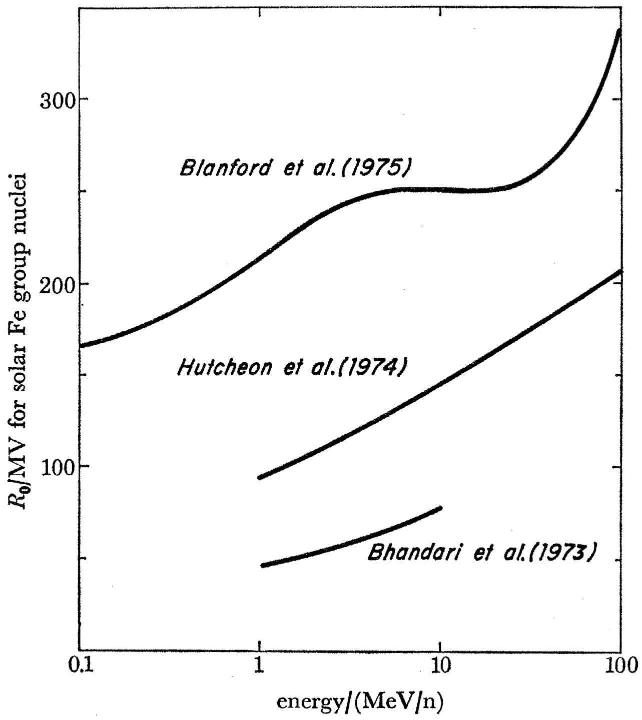


FIGURE 9

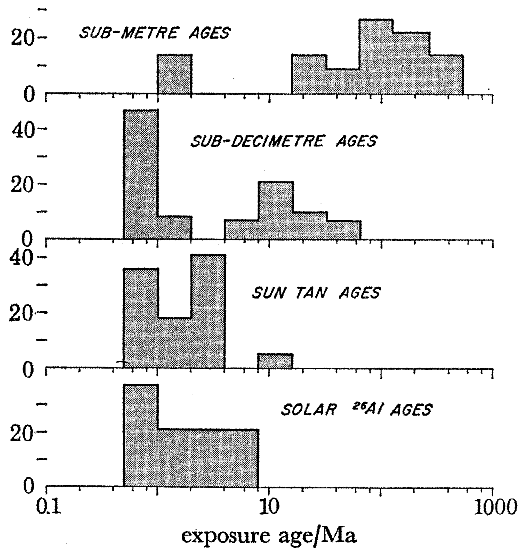


FIGURE 10

FIGURE 9. Calculated characteristic rigidity ($R_0$) values for the long term averaged iron group spectra deduced by three investigators on the basis of lunar data, for the low energy solar flare cosmic ray component.

FIGURE 10. Observed distribution of cosmic ray 'exposure ages' for lunar rocks. The approximate duration of exposure for 'burial' depths of less than 1 m and 0.1 m are given by sub-metre and sub-decimetre ages. Unshielded surface exposure ages are given by suntan and solar Al-26 ages. See text for definitions and sources of data.

## 3. Lunar regolith dynamics and implications to irradiation/evolution of meteorites

It has long been realized that the continuous bombardment of moon's surface by meteoroids holds clues to evolution of lunar surface. Pioneering studies of distribution of medium (< 1 km) and large craters by Trask (1960), Moore (1964), and Ross (1968) and Baldwin (1969) bloomed into a very rich field with the range of crater sizes now studied going down to $10^{-5}$ cm, corresponding to incident particles of mass as small as $10^{-14}$ g. Very extensive theoretical and experimental treatment of the data are now available (Gault *et al.* 1974; Horz *et al.* 1975*a*, *b*; McDonnell & Flavill 1974; Neukum 1973; Neukum & Dietzel 1971), but large gaps still exist to prevent a complete treatment of planetary data.

The great interest in lunar crater studies stems not just from the fact that precise data are now available for craters over a wide interval of sizes for several locations on the Moon; it actually


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is a realization of the fact that the lunar regolith is the only source to date of documented samples of solar system for which location and present conditions of bombardment by particles are known. Contrast this with the case of a meteorite, which clearly has evolved somewhere in the solar system while subject to cosmic ray irradiation and micrometeorite bombardment, as evinced from a variety of facts that most of the stony meteorites are brecciated, most meteorite classes have constituent grains implanted with solar wind gases (Wänke 1965; Eberhardt *et al.* 1966, Pepin & Signer 1965), solar flare tracks (Lal & Rajan 1969; Pellas *et al.* 1969; Poupeau & Berdot 1972; Poupeau *et al.* 1974) and they have been exposed to the micrometeorites (Brownlee & Rajan 1973).

One has already begun to evaluate difference/similarities between meteorites and lunar breccia: in the case of tracks (Arrhenius *et al.* 1971; Barber *et al.* 1971; Lal 1972; Pellas 1972; Bhandari *et al.* 1973*c*; Macdougall *et al.* 1974; Price *et al.* 1975), rare gas contents (Poupeau & Berdot 1972; Poupeau *et al.* 1974; Ducati *et al.* 1973; Bhattacharya *et al.* 1975; Anders 1975) and other features such as mineralogic heterogenities, petrology (Mazor *et al.* 1970; Pellas 1972).

In spite of the realization that the lunar regolith forms an ideal learning ground to contemplate meteoritic evolution, progress in this field is bound to be very slow simply because the regolith dynamics is a very complex problem demanding unfolding of the observations on craters, solar wind, spallogenic gases, tracks, etc., in a multi-dimensional network of several unknowns which contribute to mixing and physical changes within the lunar samples. Unknowns, besides being time variant, are continuous functions over several magnitudes in mass, dimension and energy.

We will confine further discussions only to important facets of regolith dynamics with bias towards observations where fossil track studies have made significant contributions to our understanding of the regolith dynamics. We will deal with 'exposure ages' of samples on the lunar surface and within the regolith, relating them to survival of rocks against fragmentation/erosion, growth and mixing of lunar soil due to cratering phenomena and finally will discuss some implications of lunar data to evolution of meteorites. The micrometeorite flux forms an integral part of these discussions but we will not go into this aspect in any detail. Reference is made to some recent papers on this subject (Horz *et al.* 1975*a*, *b*; Gault *et al.* 1974; Neukum *et al.* 1973).

### (*a*) *Exposure ages of lunar samples*

The time elapsed since the crystallization of a rock is probably one of the best defined 'age' concepts, and most other age estimates have to be qualified. Cosmic ray exposure ages based on tracks, spallogenic gases, radioactive products refer to the time spent by the rock during different time intervals, generally not defined precisely with respect to its exposure geometry. In its simplest form, the exposure age of a rock, $T$ between 0 and $t$, is given by the measured quantity $C(x)$ for a 'change' in the rock and the estimated rate of 'change', $\dot{Q}(x)$:

$$T = C(x)/\dot{Q}(x). \tag{2}$$

The quantity $C(x)$ is however related to $\dot{Q}(x)$ by the following relation for the case of production during a time period $t$ in the past:

$$C(x) = \int_0^t \dot{Q}(y, t)\, e^{-\lambda t}\, dt. \tag{3}$$

In equations (2) and (3), $x$ and $y$ respectively define in some suitable manner the effective depth of the sample within the rock at $t = 0$ and $t$. The production function, $\dot{Q}$ is generally a function of other coordinates, $\theta$, $\phi$, i.e. the exposure geometry generally is not the same in the past. The quantity $C$ defines the measured property and in its present form, equation (3) equates $C$ to the observed concentration of a radioactive nuclide in the sample. For permanent properties or changes induced in the rocks, the term $e^{-\lambda t}$ will be excluded from equation (3); equation (2) remains unchanged.

The spectral form of the production function defines the meaning of the exposure ages. In the case of solar flare induced tracks or the solar flare induced radioactivity, the integral in equation (3) contributes to $C(x)$ only for values of $t$ when the sample is exposed within a narrow depth interval, micrometres to millimetres depending on the exact nature of the measurements performed. In the case of galactic cosmic ray induced spallogenic gases, the production functions $\dot{Q}$ is not very depth sensitive up to depths of 1 m nominally, and hence if the rock did remain at such depths, the measurement of $C$ will relate to the total time spent by the rock when at depths less than 1 m. In each case, however, note that the time interval is not precisely defined unless the functional dependance is known for the variation of $\dot{Q}(x, t)$, which is generally not the case. The exposure ages calculated using equation (2) with spallogenic cases can therefore be designated as sub-metre exposure ages.

Considering the above, if a rock has had a complex irradiation history i.e. multiple exposure as it outcropped to the surface, and was further exposed on the lunar surface while subjected to fragmentation erosion, none of the radioactive or non-radioactive methods will give concordant estimates of exposure ages (Lal 1972). In general, one would expect the following inequality to hold:

$$T_{\text{s.c.r.-r.n.}} < T_{\text{f.t.}} < T_{\text{g.c.r.-r.n.}} < T_{\text{g.c.r.-s.}} < T_{\text{n.}} \tag{4}$$

where the subscripts fix the method used for determining the rock exposure age: s.c.r. = solar flare cosmic radiation, f.t. = fossil track, g.c.r. = galactic cosmic radiation, r.n. = radionuclide, s. = stable isotope, n. = thermal neutron induced isotope.

Thus for a rock which has had a varied history the regolith, in contrast to a simple history, for example recent out-cropping by crater formation of a rock from great depths where cosmic ray effects were negligible, there will be a continuum of surface exposure ages depending on the dating method employed. (A rock which yields concordant age based on different methods would be the one which was exposed to solar and galactic cosmic radiations in a given geometry throughout its exposure period.) Clearly for studying cosmic ray prehistory one must chose rocks of simple exposure history and other types of rocks for studies of lunar regolith dynamics.

In figure 10 we show the calculated exposure ages of rocks using the fossil track method which is capable of yielding at least 2 different exposure ages, the solar flare cosmic radiation produced $^{26}$Al activity method which yields the duration of exposure on the lunar surface while it was shielded by less than few millimetres or so of rock material, and the cosmic ray spallogenic noble gas method which yields sub-metre ages (duration of exposure of the rock to primary and secondary galactic cosmic ray particles within 1 m rock equivalent depths in the regolith, as discussed earlier). The two fossil track ages are the 'suntan' and 'subdecimetre' exposure ages which refer to the time spent by the rock when its present surface was shielded by less than 1 mm and 10 cm of rock equivalent, respectively. In the former case, i.e. the suntan age, for example, the exposure age determined will correspond to the time interval for which the present rock surface was exposed while subject to erosionary processes but not to any discrete fragmentations or chipping off corresponding to loss of $\gtrsim$ 1 mm. of rock surface. Bhandari *et al.* (1971); Lal (1972); Bhattacharya *et al.* (1975) give further discussion of the exposure ages.

Fossil track ages and spallogenic ages in figure 10 refer to the same group of rocks selected without bias. The selection procedure was simple; a total of 30 rocks were considered for which detailed fossil track data were available. Track data are mostly from the Indian group (see Bhattacharya *et al.* 1975 for references); for 7 rocks analysed by other groups where raw track data were available, the exposure ages were recalculated by us. For a comprehensive summary of the various rocks dated by the track method, reference is made to Crozaz *et al.* (1974). Spallogenic rare gas exposure ages for these rocks are summarized by Crozaz *et al.* (1974) and Arvidson *et al.* (1975*a*). The solar $^{26}$Al ages are however based on data for a different but unbiased set of data reported separately by Keith & Clarke (1974) for 28 and by Yokoyama *et al.* (1974) for 155 Apollo 11–17 rocks. Rocks unsaturated in solar $^{26}$Al activity were uniformly distributed in the 0.5–1.0 Ma age interval, the rest in the 1–8 Ma interval, on an ad-hoc basis.

We note that as the depth interval covered by the dating method increases, the range of exposure ages becomes wider; the 'partial' exposure ages on the surface, based on solar excess $^{26}$Al activities and fossil tracks (suntan ages) are similar in form which would not be unexpected since the two methods refer to surface exposure without chipping off of $\lesssim$ 1–5 mm of rock's surface. It would be important to compare $^{26}$Al and fossil track data for the same rock surfaces; an agreement would indicate that the solar flare tracks accumulated during the recent exposure of the rock which resulted in flare-$^{26}$Al activity.

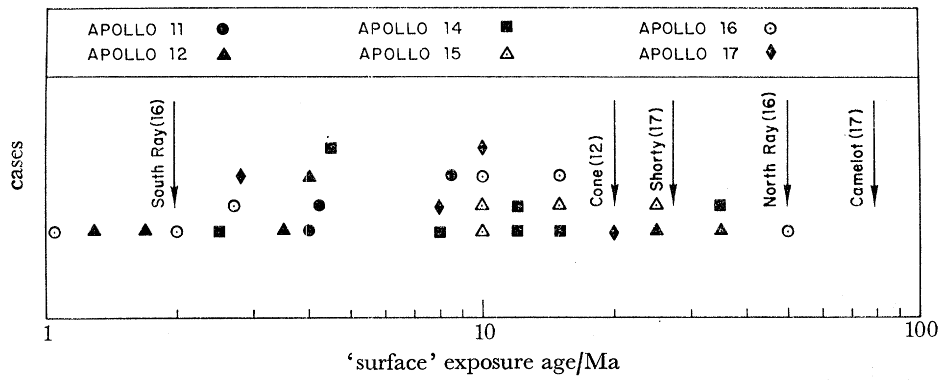


FIGURE 11. Frequency distribution of 'surface' exposure ages of lunar rocks of (5–20) cm size, based on particle track data (after Bhattacharya *et al.* 1975); the surface exposure age refers to the duration of time spent by rock on the lunar surface. Ages of five well dated lunar craters (cf. Arvidson *et al.* 1975*a*) are shown by arrows; the numbers within parenthesis of the crater name signifies the Apollo mission number.

In an attempt to learn something about the distribution in time scales involved in the recent lunar surface processes, Bhattacharya *et al.* (1975) have studied the total exposure ages of lunar rocks on the surface. They conclude that rocks found on the surface were emplaced there 2–50 Ma ago. Rocks excavated earlier do not survive destructive collision with meteoroids. Bhattacharya *et al.* (1975) also discuss, on the basis of the frequency distribution of surface exposure ages (figure 11), that majority of the rocks presently on the lunar surface were excavated in principal meteorite producing collisions leading to the bronzite and hypersthene chondrites (Wänke 1966; Zahringer 1966; Kirsten & Schaeffer 1971).

Thus it seems that records of prominent collisions in space may be well preserved on the lunar surface. Increased statistics on ages of young craters will provide very valuable information in this regard; see figure 11, where the five dated lunar features of ages below 100 Ma (cf. Arvidson *et al.* 1975*a*) are indicated by arrows.

Finally, we show in figure 12 the observed distribution of Sun-tan ages of Apollo 11–17 rocks; there seems to be a tendency for similar behaviour for rocks from a given mission, indicating that friability indices are different for rocks from different missions.

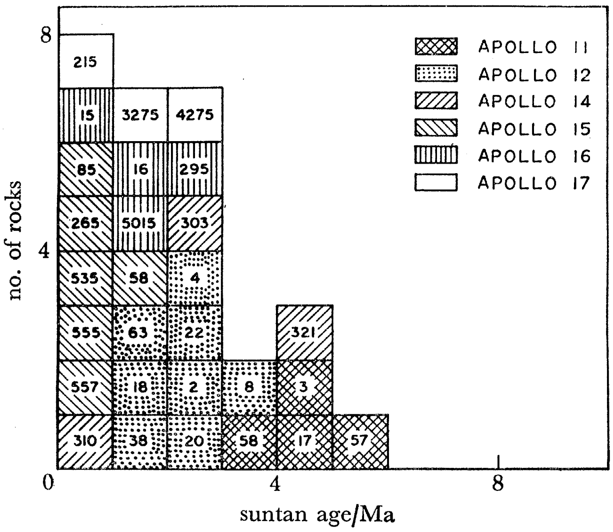


FIGURE 12

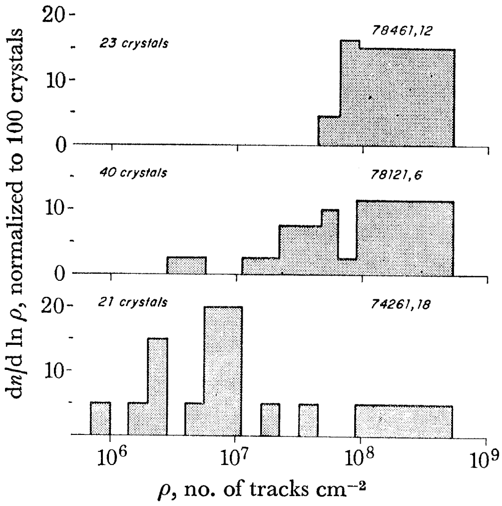


FIGURE 13

FIGURE 12. Frequency distribution of suntan ages (see text for definition) of lunar rocks from all the sample returning Apollo missions. See Bhandari *et al.* (1973*d*) and Goswami & Lal (1974) for sources of data.

FIGURE 13. Histograms showing three types of track density distributions found in lunar soil samples. (Data are due to Goswami & Lal (1974).) Grains having track densities > $10^8$ cm$^{-2}$, are uniformally distributed over the interval 1–5 × $10^8$ cm$^{-2}$.

## (*b*) *Lunar regolith growth/mixing*

The commonly observed layered structure of the soil in the lunar core tubes and the individuality of layers with respect to their track irradiation features as characterized simply by the $N_H/N$ parameter (Lal *et al.* 1970, Arrhenius *et al.* 1971), which gives the fraction of grains irradiated on the lunar surface, make it very obvious that except for a thin surface layer (< 1 cm) vertical mixing, produced by cratering phenomena, is slow relative to the deposition of new material by the same cratering processes; this was concluded long ago by Arrhenius *et al.* (1971) by examination of core and soil samples from the Apollo 12 mission. Intense vertical mixing was found to be confined to the very top layer (< 1 cm) in the case of a layer exposed for 20–30 Ma, based on the observations of track-rich grains.

Based on track density distribution characteristics (see figure 13 for three types of distributions found in lunar soils), Arrhenius *et al.* (1971) proposed a simple deposition model in which layers of certain thicknesses were exposed on the lunar surface for certain periods of time, during which time the vertical mixing did not affect grains in lower parts of the layer, where cosmic ray track accumulation proceeded during the exposure of the layer, forming the basis of the dating method. Arrhenius *et al.* (1971) postulated that deep seated unirradiated material was deposited. The observed track density distributions in soil grains were then compared with expectations for a quarter of the grains in the deposited layer; a further assumption is made here that the lower quarter of the layer remains undisturbed before occurrence of the next blanketing event. The exposure ages of the layers were calculated on the basis of observed lower quartile track density. In the event of a pre-irradiation of the deposited material, one would overestimate the time exposure of the layer at that place.

Calculated frequency distribution of model exposure ages of scoop and core-soil samples are given in figure 15. It is seen that low exposure ages ($<$ 30 Ma) occur more frequently; high exposure ages ($\gtrsim$ 50 Ma) are also suspect generally because of important contributions from roll-over, grain by grain accumulation and pre-irradiation (Bhattacharya *et al.* 1975).

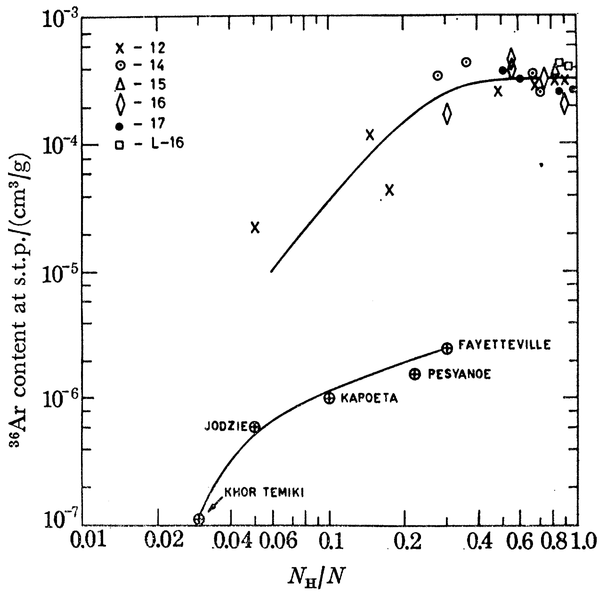


FIGURE 14. Solar $^{36}$Ar concentrations against $N_H/N$ values for lunar soil and dark portions of gas rich meteorites. For sources of data, see Bhattacharya *et al.* (1975).

The observed depth distribution of quartile track densities in individual layers seems to be quite consistent with the over-simplified layer by layer deposition model adopted. Support to the model is provided by other observations relating to petrologic features and contents of spallogenic rare gases thermal neutron produced isotopes (Goswami & Lal 1974; Crozaz 1975; Walker 1975). McKay *et al.* (1971) showed that there existed a very good correlation between petrographic data, referring primarily to agglutinate contents of soil and track based exposure ages. Production rates of agglutinates, which are formed on the 'lunar surface' have been given by Goswami & Lal (1974). Soil exposure ages and trapped solar gases in the bulk soil samples also correlate with the fraction of track rich grains (see figure 14).

However, the theoretical calculations of Arnold (1975) and Gault *et al.* (1974) would suggest that even in regions which exhibit growth, most of the layers which were deposited originally have been replaced by new layers. Thus, besides a hiatus in the time sequence, considerable horizontal and vertical mixing is expected on the basis of the cratering calculations. Track data however, do not seem to support these calculations which depend sensitively on the flux and mass spectra of cosmic projectiles, and the cratering parameters. In the case of a fair mixing, unless track annealing or incorporation of deep seated un-irradiated material plays an important role in blanketing events, one would expect much smaller range in $(N_H/N)$ values and an essentially linear $(N_H/N)$ – quartile track density relation; these expectations are not borne out by the track data (Arrhenius *et al.* 1971; Bhandari *et al.* 1973*d*; Goswami & Lal 1974). Thus, one of the challenging problems today is to understand the observed track density distributions as well as the thermal neutron produced isotope data, which can not be easily understood on the basis of Monte Carlo calculations (Arnold 1975). One has to either invoke complicated 'mixing' models or simple deposition models and it remains to be seen which one of these can more adequately explain the suite of data on mineralogy/chemical composition/isotope concentrations and cosmic ray tracks, in terms of our present day knowledge of cratering rates and phenomena.

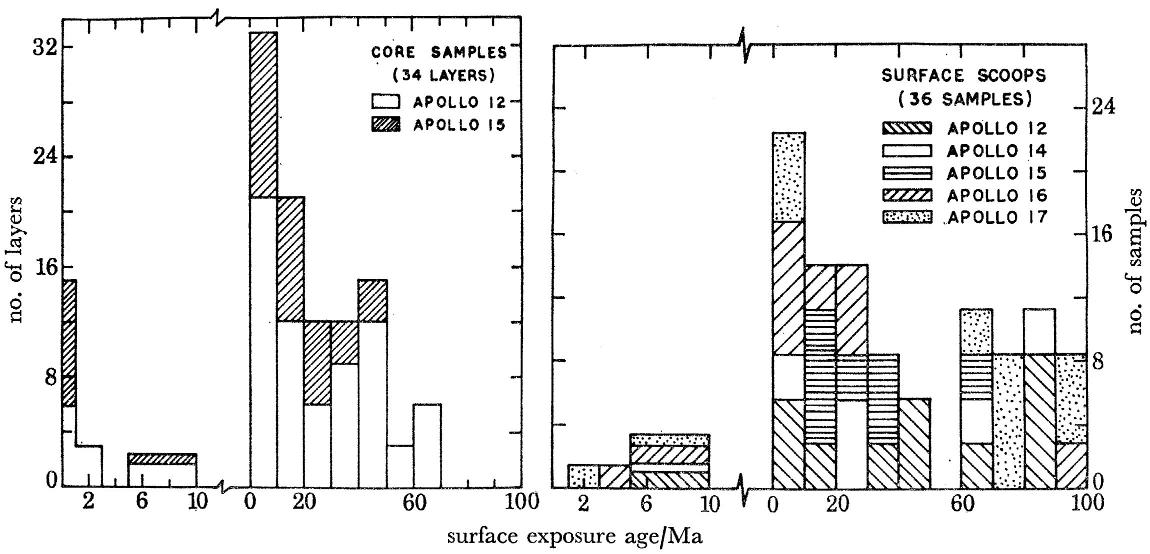


FIGURE 15. Frequency distribution of surface exposure ages of soil samples from various Apollo missions dated using the fossil track method (Arrhenius *et al.* 1971; Bhandari *et al.* 1972, 1973*d*; Goswami & Lal 1974).

The general agreement between model track ages, surface correlated features and cosmogenic effects implies an appreciable concentration of low track density grains whenever a fresh layer is deposited. Two important sources (besides the deep seated unexposed material) are (i) chips from boulders on the surface and (ii) annealed grains. Detailed discussion on this subject will soon be available (Goswami & Lal, in preparation).

An interesting observation made by Bhattacharya *et al.* (1975) is that the grain size distribution of soil samples bears a relationship with the maturity of the soil sample, although not in a unique manner. These observations must be understood in terms of fragmentation of grains, formation of agglutinates and their break up; the whole process is extremely complex but a reality (King 1975; Lindsay 1974; Bhattacharya *et al.* 1975).

At present, details of the soil deposition/mixing processes are being worked out using a great variety of techniques based on cosmogenic effects, mineralogic composition, grain size distribution, physical/chemical changes in individual soil grains, simultaneous observations of craters and solar flare tracks, etc. For comprehensive recent discussions, see Arnold (1975), Bhattacharya *et al.* (1975), Bibring *et al.* (1975), Crozaz (1975), Crozaz *et al.* (1975), Duraud *et al.* (1975), King

(1975), Price *et al.* (1975), and Lindsay (1974). Theoretical investigations of mixing and deposition are simultaneously in progress (Arnold 1975; Arvidson *et al.* 1975*b*; Duraud *et al.* 1975; Gault *et al.* 1974).

To a student of cosmochronology, lunar soil presents a fair hope for the study of time sequence of cosmic phenomena back to 1–2 Ga in the past; the record is certainly obliterated and not clean, but seems usable. Studies, for instance, of prehistory of cosmic rays, secular changes in the meteoroid flux (cf. Lindsay 1975) have been made, among others. The lunar soil is thus merely not a sample which has been subjected to intense cosmic forces which have completely altered it, allowing a study of these forces, but it has also arranged itself in a certain manner which should provide stratigraphic type analyses.

### (*c*) *Implications of data on exposure ages of lunar samples and regolith dynamics to evolutionary history of meteorites*

As was pointed out earlier in §3, one of the important applications of lunar studies was towards delineating certain aspects of evolutionary history of meteorites. It becomes clear from preceding discussions that these aspects relate to:

(*a*) Duration of exposure of the meteorite and its individual grains to cosmic radiation during its recent and early history, before compaction,

(*b*) Formation of craters, agglutinates, and other so called 'surface-correlated' phenomena describing lunar surface processes,

(*c*) The flux and energy spectrum of charged particle radiation responsible for pre-compaction irradiation observed in certain meteorites: for brevity, we will designate it here as p.c.i. and the normal cosmic ray *irradiation* of meteorites which occurs during their orbital journey prior to their capture by the Earth as o.i.

It would be most important to understand the conditions under which p.c.i. occurred. Lal & Rajan (1969) and Pellas *et al.* (1969) considered two possibilities, p.c.i. occuring in space or on the surface of a parent body. However it later seemed preferable to the author (Lal 1972) to consider the former possibility as the most likely one considering the lunar data (Lal *et al.* 1970; Arrhenius *et al.* 1971) and the prominent differences between irradiation characteristics of lunar and meteoritic grains. Lal (1972), in terms of the then existing theoretical understanding of accretionary processes, considered Alfven's jet-stream model as an interesting method of achieving irradiation and compaction. Later on, Macdougall *et al.* (1974) made several interesting observations on Fayetteville and Kapoeta meteorite and suggested that the p.c.i. must have occurred on a regolith. Subsequent investigations by Poupeau & Berdot (1972), Brownlee & Rajan (1973), Bhandari *et al.* (1973*c*); Poupeau *et al.* (1974), Rajan *et al.* (1974), and the recent work of Price & Macdougall has since added considerable new useful data on p.c.i. (Price *et al.* 1975; Kothari & Macdougall 1975; Macdougall 1975; Macdougall & Price 1974). We now discuss some prominent differences between meteorites and lunar breccias and mention some facts which must be considered in the present type of study.

(1) The grain size distributions of moon and meteorite samples are very different; the differences being outside the range of fluctuations observed between the various lunar samples from different missions (Bhattacharya *et al.* 1975).

(2) The fraction of track-rich grains ($N_H/N$) observed in lunar samples quite often exceeds 0.7, but the trapped solar wind gas content saturates in samples where this fraction exceeds 0.4.

In meteorites, $N_H/N$ values are so far observed to be $\leqslant 0.3$ (figure 14). The 'gas' content of meteorites is appreciably lower compared to lunar samples (Anders 1975), but the $N_H/N$ observations clearly point to the fact that this is not due to merely a larger dilution with un-irradiated grains in the case of meteorite samples. Since the irradiation time to form a track rich grain is deduced to be an order of magnitude greater than that for saturating a grain with solar wind, and this will hold for the past as long as the solar flare to solar wind flux is the same as at present, information on the abundance of track rich grains suffices to predict the minimum expected fraction of grains irradiated to saturation with solar wind. Hence a higher cratering rate as postulated by Anders (1975) can not, by itself explain the smaller gas contents of meteorites. (For discussion of other explanations which may be invoked to reduce the trapped amount of solar wind in meteorites, see Bhattacharya *et al.* 1975.)

At present, the simplest hypothesis, consistent with observations is that the ratio of solar wind to solar flare flux remained invariant in the past, and that not only the gas contents of meteorites are smaller, the fluences due to solar flare radiation are also lower in meteorites (Bhattacharya *et al.* 1975).

It may be mentioned that Anders (1975) has discussed the interesting possibility of irradiation of meteorites at large distances from the Sun in which case the solar wind flux itself would be much lower, e.g. by an inverse square law dependance. In this situation the inverse square law which is expected to hold outside the solar plasma modulation zone will also be applicable for the flare radiation. Thus our conclusion seems to support Anders' suggestion that some meteorites may have received p.c.i. at large distances. However, other situations can lead to the same result, e.g. higher erosion rate. Distinct clues to the distance of p.c.i. have yet to be delineated.

(3) The irradiation features of lunar grains comprise a much wider range of patterns, with respect to track densities on different faces of grains, compared to meteoritic track rich grains (Lal 1972; Macdougall *et al.* 1975). Except for carbonaceous chondrites (Macdougall & Price 1974), isotropic irradiation features are commonly observed in the case of meteorites.

(4) The spallogenic exposure ages of lunar samples show a large spread going up to 0.5 Ga for several rocks which were recently brought to the surface (figure 10). It is well known that the cosmic ray exposure ages of stone meteorites (gas rich or otherwise), which are usually considered to represent primarily the exposure age while in orbit, prior to capture (o.i.), are usually small ($< 20$ Ma) and show a spread going to very small values ($< 1$ Ma). The interesting question which we pose here is: If the gas rich meteorites originated on a parent body with a regolith, where is the evidence for their irradiation while they were stored in the regolith? Postulating a high cratering rate in the past does not ease the dilemma because one knows that an appreciable fraction of grains in these meteorites did receive flare irradiation. Clearly, after irradiation to solar wind and flare particles, it would be necessary to 'store' the meteorites at some place where cosmic ray irradiation effects are small, e.g. in deeper regions of a parent body.

The above facts open up interesting questions regarding the relative flare to solar wind fluxes during p.c.i. and the conditions under which p.c.i. proceeded; however, it becomes clear that in the case of meteorites, one must deal with much lower velocity phenomena compared to that observed on the Moon, as inferred from the grain size distributions (Bhattacharya *et al.* 1975) and track irradiation features (Lal 1972). It seems difficult at present to conclude anything beyond this, e.g. whether irradiation occurred on a regolith or in free space. Favourable conditions for low velocity accretion/irradiation occur in the asteroidal jet-streams, which encompass a whole range of situations which exist in the solar system (Alfven & Arrhenius 1975), including small asteroidal bodies.

## 4. Ancient large scale lunar magnetic field – possibility of its detection from observations of solar flare tracks in ancient 'preserved' samples

Based on analyses of fossil tracks, it is found that the lunar regolith, down to the deepest depths sampled so far (2.5 m drill core from Apollo 15 site, Bhandari *et al.* 1973*d*) contains an appreciable proportion of grains which have been heavily irradiated on the lunar surface, without any shielding, with solar flare heavy nuclei of $< 10$ MeV/n. We ask ourselves what type of track profiles will be seen in surface irradiated grains if some large scale magnetic field was present at the time of irradiation; in other words can the fossil track method be used to detect ancient fields? (For earlier discussions on this subject, see Lal (1974), pp. 410–411.) This question has particular significance now in view of the recent work of Runcorn and his colleagues who have put forward the hypothesis that possibly the Moon had a large scale magnetic field in its early history (Stephenson *et al.* 1975).

Apollo 15 subsatellite measurements have shown that the present day global lunar magnetic field is very weak, corresponding to an upper limit of $1.3 \times 10^{14}$ T ($1.3 \times 10^{18}$ G) $cm^3$ for the permanent dipole moment in the orbital plane (Russell *et al.* 1974). This would result in an equatorial surface field of only 0.025 nT, considerably smaller than the regional magnetic fields of the order of 10 nT on scale sizes of tens of kilometres (Russell *et al.* 1974). Nevertheless, the experimental and theoretical considerations put forth by Runcorn and his group suggest the existence of an appreciable ancient lunar field due to an internal source which gradually decreased in strength. Stephenson *et al.* (1975) suggest that the surface field decreased from 1.3 Oe to 0.05 Oe† over the period 3.9 to 3.2 Ga. There exists however no consensus on the view point (Fuller 1972; Strangway *et al.* 1973), namely that the magnetic field was global in character.

Considering however that the interpretation of Runcorn is valid (plausible), we have deduced the magnitude of expected effect on the solar flare track density profile in surface irradiated grains.

The vertical Störmer cut-off rigidities at 0, 30, 45 and 60° for equatorial fields of $10^{-4}$–1 Oe, assuming a dipolar field, are shown in figure 16*b*. The rigidity–kinetic energy relationship, taking into account the effective charge (Heckman *et al.* 1960) is shown in figure 17 for protons, $\alpha$-particles $^{56}$Fe and $^{80}$Kr nuclei. The approximate validity of the cut-off calculations, figure 16, is ensured only if the magnetic field is strong enough so that a bow-shock results. Even in the presence of a lunar magnetosphere, particles of rigidity lower than the Störmer cut-off values will be allowed at high latitudes ($\lambda > 60$–$70°$) on the sun-lit side where the magnetic lines of force are pulled out towards the antisolar direction (cf. Frank & Allen 1964). Thus the minimum condition for the existence of a cut-off or screening of low energy flare particles will correspond to the case when a bow-shock exists on the solar side. The condition for this to happen is easily obtained by balancing the pressure due to lunar magnetic field with that due to solar wind (Choe *et al.* 1973):

$$r_s/r_M = 1.07\,[B_0^2/(4\pi\, m_p\, nv^2)]^{\frac{1}{6}}$$

† 1 Oe corresponds to $10^3\,(4\pi)^{-1}$ A $m^{-1}$.

where $r_s$ is the radius of the so-called 'stagnation point', which is approximately the radius of magnetopause on the sun-lit side, $r_M$ is the radius of the Moon and $B_0$ is the equatorial (magnetic) lunar dipole field, $m_p$ is proton mass; $n$ and $v$ are respectively the number density and velocity of protons in the solar wind. The calculated values of radius of the stagnation point, based on $n = 4\ cm^{-3}$, $v = 5 \times 10^7\ cm\ s^{-1}$, are plotted in figure 16*a* as a function of $B_0$. A magnetopause is formed only when the equatorial surface field exceeds $3.65 \times 10^{-4}$ Oe. The variation of $(r_s/r_M)$ is not a sensitive function of the solar wind flux; a $\pm 30\%$ uncertainty in solar wind flux corresponds to a $\pm 5\%$ error in the radius of stagnation point. The minimum value of $B_0$ above which a bow shock results, however varies as $v\ (n)^{\frac{1}{3}}$.

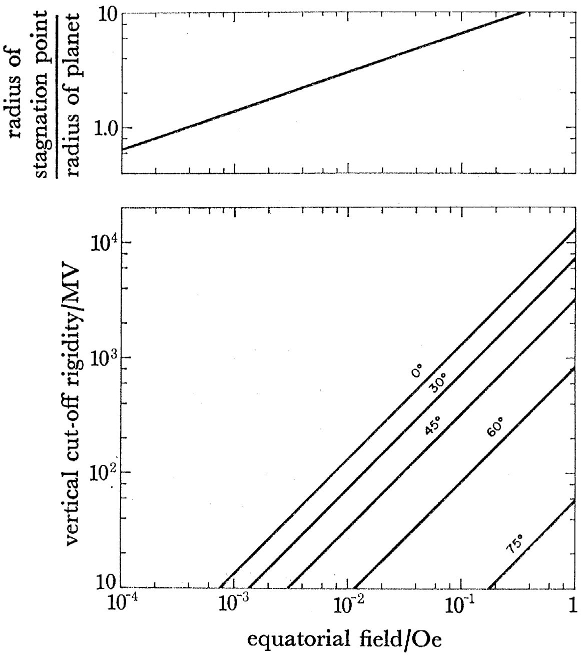


FIGURE 16

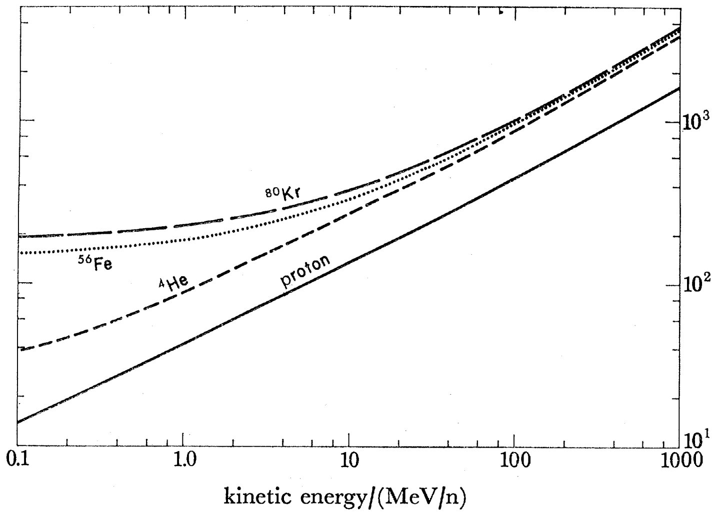


FIGURE 17

FIGURE 16. The calculated vertical Störmer cut-off rigidities are plotted in the lower figure for different geomagnetic latitudes and equatorial surface field intensity arising from a dipole. In the upper figure, the radius of stagnation point, in units of radius of a planet assumed to have a dipolar field, is plotted as a function of equatorial magnetic field. Values smaller than 1.0 are of no significance, of course.

FIGURE 17. Kinetic energy–rigidity relation for $^1H$, $^4He$, $^{56}Fe$, and $^{80}Kr$ using effective charge values, based on the relation given by Heckman *et al.* (1960).

The above over-simplified model calculations seem to be valid, considering the recent detection of the magnetosphere of Mercury for which Mercury I data yield a planetary dipole moment of $5.1 \times 10^{22}$ G cm³, oriented 7° from the orbit normal (Whang & Ness 1975; Ness *et al.* 1975). This dipole moment corresponds to a nominal value of only $3.5 \times 10^{-3}$ Oe for the (magnetic) equatorial surface field intensity. Thus the approximate validity of equation (1) has been checked for the case of Earth and Mercury, i.e. over a range of $3 \times 10^{-3}$–$3 \times 10^{-1}$ Oe for the equatorial surface magnetic field intensity.

Based on figures 16*b* and 17, we have generated another more convenient graph (figure 18) which relates the minimum kinetic energy of allowed particles with the equatorial field intensity. In the case of iron and heavier nuclei, most of the solar flare tracks arise from these nuclei in the kinetic energy interval 0.5–10 MeV/n (see figure 1); it then follows that for any appreciable change to occur in the 'solar' track profile, due to non-access of flare particles to the lunar surface, the surface equatorial field would have to lie in the interval $10^{-2}$–$10^{-1}$ Oe, considering a wide range of 0–60° lunar magnetic latitudes. At a given latitude, the interval is much smaller; at 30°, the equatorial field values would have to lie between 2 and $4 \times 10^{-2}$ Oe. If the field is smaller there will be no effect on the incident flux of the lowest energy track forming nuclei. If the field intensity is higher, the solar flare nuclei will be totally excluded and there will be no means of detecting the presence of this field.

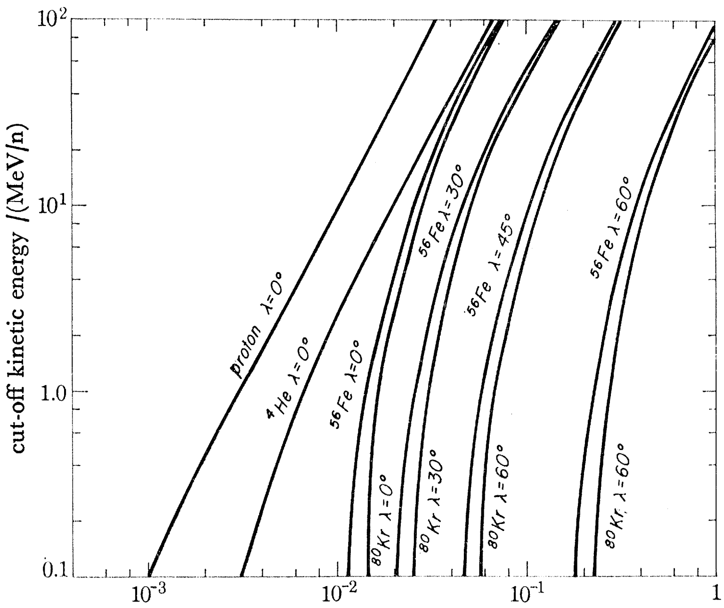


FIGURE 18

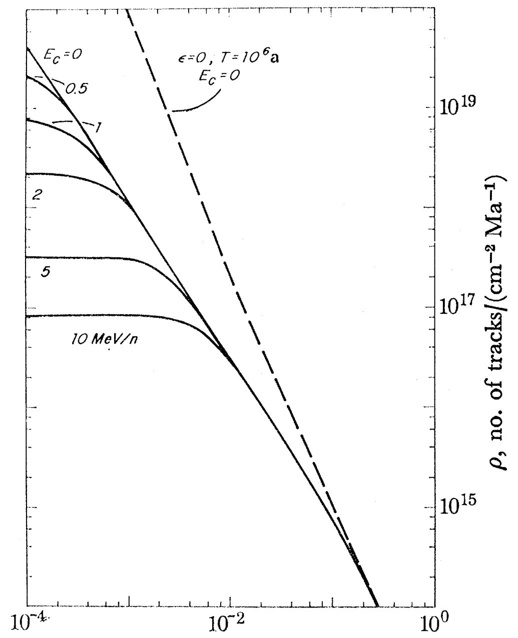


FIGURE 19

FIGURE 18. Calculated values of Störmer vertical cut-off kinetic energies for P, $^4$He, $^{56}$Fe, and $^{80}$Kr as a function of equatorial magnetic field intensity for a dipolar field.

FIGURE 19. Calculated track densities for a power law differential kinetic energy spectrum of iron nuclei with a slope of (−3.0), for some hypothetical flux. The dotted line shows track production rate for no erosion ($\epsilon = 0$) and no lower energy cut-off in the spectrum. Other graphs represent cases when there is a cut-off, at 0.5, 1, 2, 5 and 10 MeV/n; the erosion rate is $5 \times 10^{-2}$ cm/Ma in each of these cases.

Stephenson *et al.* (1975) deduce a mean field decline rate of $1/(0.2 \times 10^9)$ a$^{-1}$ for the time period 3.2–4.0 Ga. Time spans of 0.14 and 0.5 Ga are expected for the time for which the surface field would remain within 2–$4 \times 10^{-2}$ Oe and $10^{-2}$–$10^{-1}$ Oe respectively. Thus the rate of field decline is not too sharp and there exists a fair chance of finding samples irradiated at lunar surface during the time periods of interest.

As illustration we give in figure 19, the relative track production rates as a function of depth in a large lunar rock exposed freely on the lunar surface, for different assumed cut-offs in the spectrum due to a global lunar magnetic field. These calculations are based on an erosion rate of $5 \times 10^{-8}$ cm a$^{-1}$. The effect on the track profile is quite marked and it should be possible to see effects of magnetic field in grains exposed only during periods when the field was present.

So far, we have tacitly avoided the discussion on the availability of lunar samples suitable


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for the magnetic test. Ideally speaking one would like to have samples which cooled down on the lunar surface and were then irradiated with the solar flare nuclei. In practice, however such samples can hardly be found; the time of crystallization and irradiation will generally be different. Another important source of complication arises due to the fairly high probability of a given grain being irradiated more than once on the lunar surface during its life time after cooling. Considering these points one concludes that grains in breccias, compacted 3–4 Ga ago, would be ideal for the magnetic tests rather than loose grains in the regolith; in the latter case, probably lunar samples dating back to 3–4 Ga have not yet been collected. Shock metamorphism (Williams 1972; Hintenberger *et al.* 1975) leads to gas-losses and allows dating of compaction date of breccias. However, care should be exerted in selecting samples where the track record itself has not been wiped off due to shock annealing (Macdougall *et al.* 1973). Alternatively, one may study fossil tracks in breccias selected at random and if a magnetic field is detected in some samples, one could attempt to determine compaction ages of those samples. If the rock is older than $\simeq$ 4 Ga the fission track method based on the excess $^{239}Pu$ fission track method (Kothari & Macdougall 1975) can be used to date the time of compaction which may be taken to approximately correspond to the time of irradiation of the grains.

We may also note here that a very interesting situation arises if one can establish that some lunar breccias contain solar flare fossil track records but do not contain any solar wind gases; it would have to be established of course that solar wind gases were not lost due to shock metamorphism. Because in this case it would imply that the whole sample was irradiated on the lunar surface whilst solar wind was excluded but not the more energetic flare ions. Observations of this type would definitely establish the presence of large scale ancient lunar magnetic fields of the order of $5 \times 10^{-4}$ Oe or larger, if the scale size of the magnetic regions is 100 km or smaller.

Thus, it seems that combined studies of solar wind and solar flare tracks should in principle permit one to obtain proof for the presence of, any large scale lunar magnetic field present in the past when the magnetic field intensity on the surface was in the region of $10^{-2}$–$10^{-1}$ Oe; a lack of evidence will however not constitute any result.

## 5. Concluding remarks

The capability of learning about the history of solar activity, restricting here to processes relating to acceleration of solar wind and flare particles, and about the secular variations in the galactic flux of higher energy cosmic ray particles, has been clearly demonstrated by the lunar and meteoritic studies. Definite information on these aspects of charged particle environment in lunar and meteoritic space is of considerable importance in solar physics and astrophysics. For example, a continued steady flux of particles from Sun during its entire history would place important restrictions on time scales in the mixing processes within the Sun. The consequences of a sluggish mixing in the Sun, on time scale of million years have recently been discussed (Rood 1972; Ezer & Cameron 1972), following a suggestion of Fowler (1972).

Lunar studies are yet useful for another important reason – to learn what happens when matter is subjected to a bombardment with nuclei and particles of different dimensions. Since such processes play an important role in evolution of objects in the solar system, and since the lunar regolith is the only documented material for such studies, the lunar soil and rock samples have attained an important status in the field of solar system astrophysics.

The present status of our understanding the charged particle environment or dynamics of accretion/fragmentation in space is rather poor but a wide range of important problems of great complexity are clearly realized. This is a happy situation.

I am extremely thankful to J. R. Arnold for discussions and helpful criticisms and to R. Gall and S. K. Runcorn for valuable discussion regarding the lunar magnetic field and its implications. Section 4 in this paper, dealing with the possibilities of detecting ancient lunar dipolar (or a large scale) magnetic field, was motivated by encouraging remarks made by Professor Runcorn at one of his recent lectures given at La Jolla. For helpful criticisms on the text, I am grateful to N. Bhandari, J. N. Goswami and J. D. Macdougall. I am also grateful to J. N. Goswami for his valuable assistance and collaboration in many phases of the work presented here.

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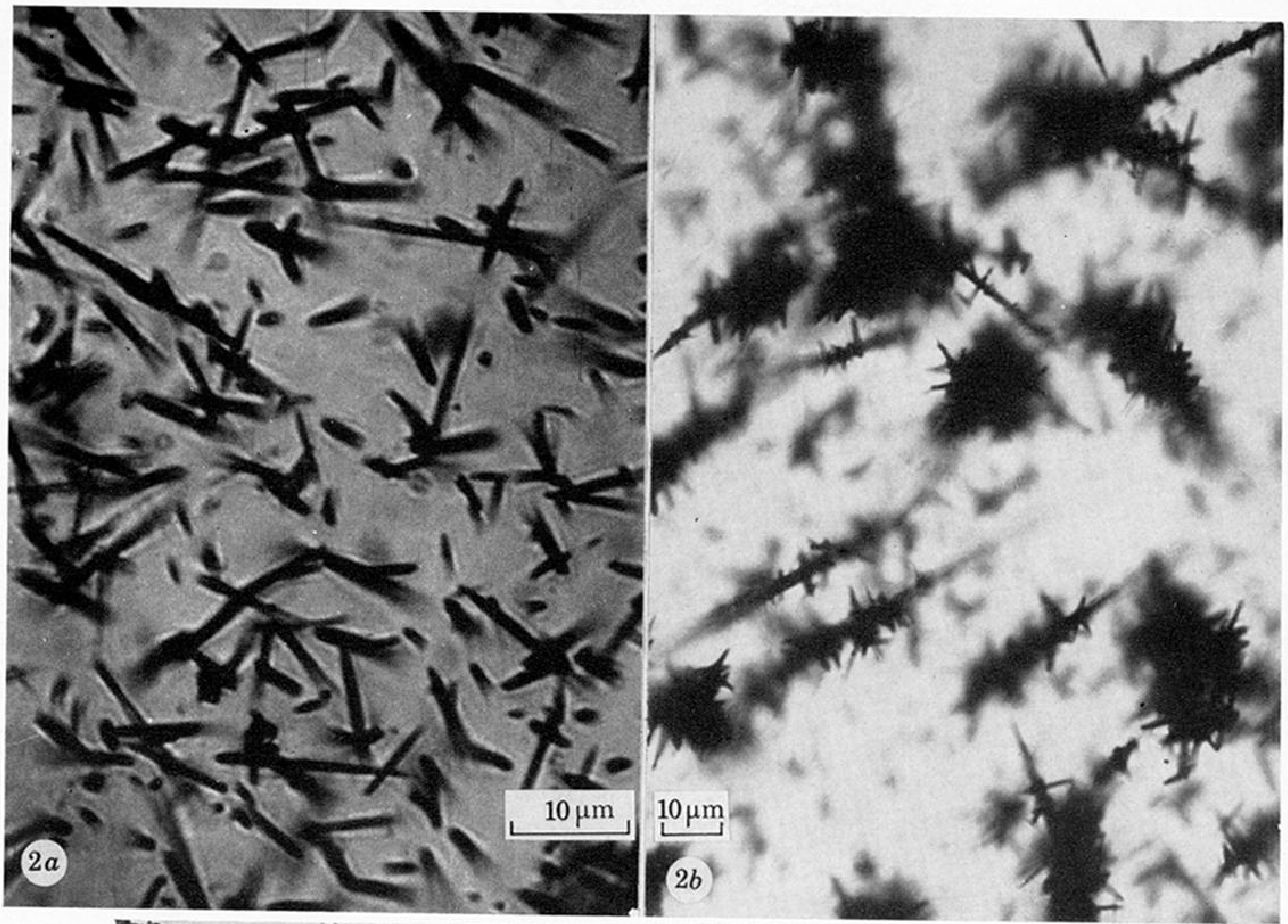


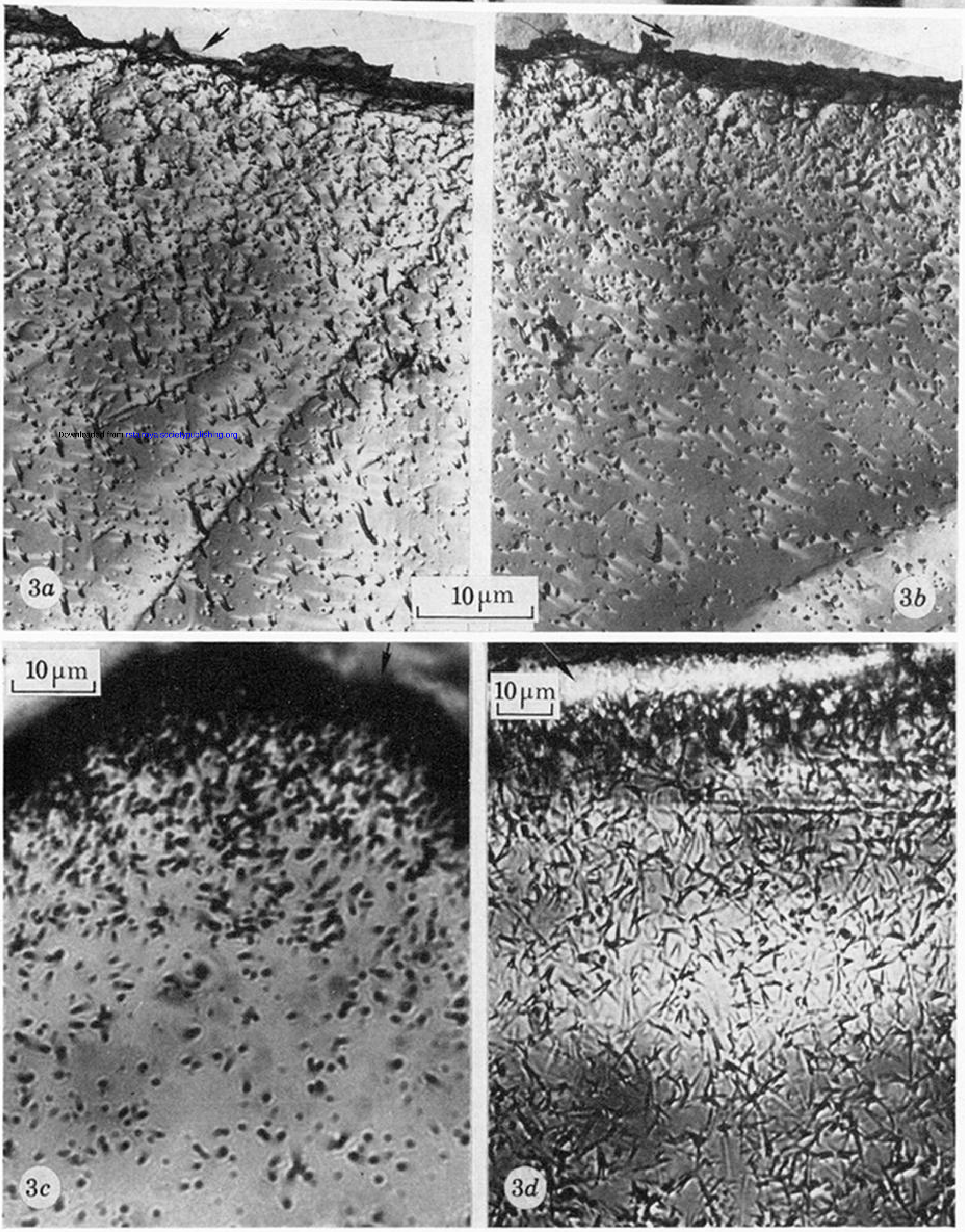




FIGURES 2 AND 3. For description see opposite.