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

Long-Term Variations in the Cosmic-Ray Flux [and Discussion]

D. Lal and H. Elliot

Phil. Trans. R. Soc. Lond. A 1975 **277**, 395-411
doi: 10.1098/rsta.1975.0006

Phil. Trans. R. Soc. Lond. A. **277**, 395–411 (1974) [395]
Printed in Great Britain

Long-term variations in the cosmic-ray flux

By D. Lal
Physical Research Laboratory, Navrangpura, Ahmedabad-9, India

[Plates 14 and 15]

The present-day information on the temporal and spatial variations in the flux and chemical composition of cosmic-ray protons and multicharged nuclei during certain intervals of time, since the beginning of the Solar System, is discussed. This information has been deduced on the basis of analyses of isotopic changes and alterations in the crystalline matrix of meteoritic and lunar materials. Most of the samples analysed were exposed to cosmic radiation during the recent time period, 0–10 Ma B.P. and some during 100–1000 Ma B.P. Limited data are also available for the time period soon after the formation of solid objects in the Solar System, i.e. *ca.* 4500 Ma B.P., based on analyses of certain meteorites. The cosmic-ray parameters deduced are for the 1–3 AU space and are average values for time periods of 10^5–10^7 a for protons, α-particles, v.h./v.v.h. nuclei in the kinetic energy interval (1–1500) MeV/nucleon.

The archaic cosmic-ray data provide information on the long term average features of acceleration of protons and heavy nuclei by the Sun and on the relative contributions of solar particles to the total cosmic-ray particle population at 1 AU. The implications of absence of any marked time variations in the flux and energy spectra of protons v.h. ($Z \geqslant 20$) and v.v.h. ($Z \geqslant 30$) nuclei are discussed briefly in relation to cosmic-ray sources and propagation.

Introduction

Along with developments in recent years in the techniques for the study of contemporary cosmic radiation, simple but reliable high resolution techniques have been developed for the study of the archaic record of cosmic radiation during epochs going back to the beginning of the Solar System. The development of the isotopic method of studying the long term history of cosmic-ray protons during the 1950s was followed in the next decade by the application of the fossil track method (Fleischer, Price & Walker 1967*a*) to meteorites and lunar samples. Etchable tracks form in the common rock minerals only due to multicharged nuclei of $Z > 20$. Observations of track densities and track lengths suffice to obtain both the energy and charge spectrum of these nuclei.

Also recent improvements in the methods of studying cosmogenic isotopic changes and their application to lunar samples provided new and accurate information on the prehistory of protons and α-particles at 1 AU. In the case of some solar flares during 1969–71, it became possible to make an intercomparison between results for protons, α-particles and v.h. nuclei based on the archaeological technology with those based on cosmic-ray particle detectors. The good agreement between these data has given credibility to the techniques used to study the prehistory of cosmic radiation.

The two phenomena which allow delineation of the cosmic-ray records preserved in extra-terrestrial samples, or on the Earth, are:

(i) production of isotopes, both stable and radioactive, in the target matrix due to nuclear interactions, and

(ii) solid state damage of the crystalline structure of constituents in the target matrix as a result of ionization losses suffered by multicharged cosmic-ray nuclei.

These *cosmogenic* effects have been extensively studied in meteorites and in lunar samples; on the Earth, a large number of cosmic-ray produced isotopes have been detected and their distribution in the various geophysical processes has been studied. We will concern ourselves here primarily with the problem of determining ancient fluxes and chemical composition of cosmic-ray particles based on the study of extra-terrestrial samples; reference is made to the review article by Lal & Peters (1967) for discussions of cosmic-ray produced radioactivity on the Earth.

Deductions on ancient proton fluxes based on studies of meteorites were first presented by Arnold, Honda & Lal (1961). For reviews prior to the lunar studies, reference is made to Geiss, Oeschger & Schwarz (1962), Lal (1965) and Honda & Arnold (1967). For a recent survey of lunar work on cosmogenic radioactivity, reference is made to Lal (1973). In the case of solid state damage studies, reference is made to Fleischer *et al.* (1967*a*) and Lal (1969) for the pre-lunar epoch, and to Lal (1972, 1973) and Comstock (1972) for recent work with lunar samples.

In view of the fairly extensive earlier coverage of the subject of cosmic-ray archaeology, we will not go into any details of the bases of the methods used except to point out the salient features with respect to their range of applicability, limitations, etc.

TABLE 1. 'PARTICLES' AND THE 'ENERGY INTERVAL' FOR WHICH INFORMATION IS AVAILABLE TODAY ON THE PREHISTORY OF COSMIC RAYS

particle	kinetic energy interval MeV/nucleon	method† radio chemistry	method† fossil track	sample better suited meteorite	sample better suited Moon
proton	500–2000	X		X	
proton	5–200	X			X
α	2–200	X			X
v.h. ($Z > 20$)	500–1500		X	X	
	30–500		X		X
	1–30		X		X‡
v.v.h. ($Z \geqslant 30$)	500–1500		X	X	
	30–500		X		X
	5–30		X		X‡

† It may be mentioned here that recently the thermoluminiscene method has been applied by Hoyt *et al.* (1973) for the estimation of low energy solar proton fluxes ($E < 200$ MeV).

‡ Individual grains of 0.01–0.1 cm size from the lunar regolith are studied for the delineation of the cosmic-ray record (Lal, 1972; Bhandari *et al.* 1973*a*, *c*).

In table 1 we have summarized the type of information currently available for cosmogenic studies for particles in different energy intervals. It is easy to appreciate the ranges of energies defined in table 1 if one considers the residual ranges of the various particles of interest: representative values are listed in table 2 for protons, helium, iron and xenon nuclei at a few energies relevant to our work.

The threshold for nuclear reactions induced by protons and the energy loss due to ionization limits one to studying proton (or α) fluxes above 2–5 MeV/nucleon. The low energy region, 5–100 MeV/nucleon is easily studied by analysing radionuclides of different threshold as a function of depth in a rock (Lal, Rajan & Venkatavaradan 1967; S.H.R.E.L.L.D.A.L.F.F. 1970) and the Moon samples are clearly more suited for a study of this energy region. With meteorites, the lowest energy region studied was about 50 MeV in the case of St Severin (Amin *et al.* 1969). The lunar work for protons of energy above 5 MeV is quite extensive and very detailed information on the flux and spectra of protons is available due to the work of several groups. This information, because of the existence of low threshold radioactive isotopes which can be conveniently produced from fairly abundant target species, e.g. ^{56}Co (half-life = 77 days), ^{55}Fe (2.5 a), ^{22}Na (2.6 a), ^{26}Al (7.4×10^5 a) and ^{53}Mn (3.7 Ma), is available for recent and olden times. ^{56}Co is very suitable for the study of the integrated fluxes in single flares which occurred within a year of a given Apollo mission. The composition of lunar samples is quite different from chondritic meteorites. In some cases, this has been of significant advantage to cosmic-ray archaeologists. For example, ^{59}Ni which is produced in meteorites in nuclear reactions induced by protons and other particles in iron, cobalt and nickel, is produced primarily by the ^{56}Fe (α n) ^{59}Ni reaction in lunar samples; the abundances of cobalt and nickel are very small in the lunar samples analysed (Reedy & Arnold 1972; Lanzerotti, Reedy & Arnold 1973).

Table 2. Approximate residual ranges of protons and multicharged nuclei in typical rocks

kinetic energy MeV/nucleon	residual range of particle in typical rock/cm: proton or α	iron	xenon
1	10^{-3}	7×10^{-4}	9×10^{-4}
10	5×10^{-2}	7×10^{-3}	7×10^{-3}
100	3	2.5×10^{-1}	1.5×10^{-1},
1000	120	10	5

Coming to fossil tracks, analogous to the case of proton spectra, the lunar samples are ideally suited for the study of low or medium energy v.h. and v.v.h. nuclei, 1–500 MeV/nucleon (table 1). Etchable tracks form near the end of range of the particle and thus for a track observed at a depth, X, in a rock, the primary energy of the nucleus corresponds approximately to that of a particle having a residual range, X. In table 2, we have listed the residual ranges for iron and xenon nuclei in typical rocks. It can be seen that for a study of v.h. and v.v.h. nuclei of energy below 10 MeV/nucleon, whose range is less than 100 μm, one has to examine samples which are exposed freely on the lunar surface, without any shielding. Also for this study, one can examine grains of size exceeding 100 μm. Samples suitable for this study are available in plenty among the lunar samples brought by the Apollo and Luna missions. In fact, a study of grains in the lunar core samples even allows one to deduce the time variation in fluxes of v.h. and v.v.h. nuclei, time-averaged over periods of the order of 10^5–10^7 a and going back to periods of the order of 10^9 a. This possibility has recently been explored (Bhandari & Padia 1974) and arises from the fact that lunar soil is often found to be well stratified and in a few core samples studied, indeed the various cosmogenic data point to an essentially layer by layer deposition of the various strata in the past *ca.* 1 Ga (Arrhenius *et al.* 1971; Bhandari *et al.* 1972*a*; Imamura, Finkel & Wahlen 1973).

The low energy bombardment differs in character from that at high energies, particularly in the case of fossil tracks. The solid state damage often becomes very excessive (because of higher particle fluxes at low energies) so that it is of course not possible to study the tracks using an optical microscope (Macdougall *et al.* 1971). Reference is made to papers by Dran, Durriew, Jouret & Maurette (1970); Barber *et al.* (1971) and Macdougall, Rajan, Hutcheon & Price (1973) for some work dealing with very low energy heavy nuclei (< 1 MeV/nucleon).

A problem common to the study of the archaeology of cosmic radiations by means of meteorites or lunar samples is that arising from uncertainties in the duration of exposure and the irradiation geometry during this exposure. Micrometeorite bombardment and solar wind irradiation causes continuous erosion of the surface. All this makes the delineation of the cosmic-ray record partly model dependent. The extensive studies of a large number of lunar rock and soil samples by several track groups have led to a rapid elucidation of the principal lunar surface phenomena and in turn to a better understanding of the cosmic-ray archaeology. Based on the current models (cf. Bhandari *et al.* 1972*a*; Crozaz *et al.* 1972), we estimate mean erosion rates of the order of 5×10^{-8} cm/a. Consideration of the cosmic-ray spectra, leads to effective irradiation time periods for v.h. nuclei of energy below 10 MeV/nucleon which are considerably shorter than 1 Ma. Only at energies above 100 MeV/nucleon, the erosion effects are negligible for typical cosmic-ray exposure ages as encountered in the case of meteorites or lunar rocks.

The approximate erosion controlled model irradiation time periods are summarized below for v.h. and v.v.h. nuclei:

energy / MeV/nucleon	effective erosion controlled irradiation period/a
1	2×10^4
10	2×10^5
100	5×10^6
1000	10^8

The space-time boundaries normally accessible with meteorites and lunar rocks are given below:

meteorites (1–3 AU)	present – (5–10) Ma: chondrites
	present – (50–100) Ma: iron meteorites
	4.5 Ga ago: gas rich meteorites
lunar samples (1 AU)	present – (1–5) Ma: lunar rocks
	present – 500 Ma: lunar soil samples
	3–4 Ga ago: lunar breccias

Having discussed the principal cosmogenic effects in extra-terrestrial samples and the type of information which is currently available on the archaic particle fluxes and energy spectra, we will now discuss the results of analyses to date of radionuclide and fossil track data. (For recent comprehensive surveys and evaluation, reference is made to Lal 1972, 1973.)

Ancient proton and α-particle energy spectra

Several flares occurred before the Apollo missions and it became possible to make an intercomparison between the experimental values of the recent time averaged flare fluxes and spectral shapes based on radiochemical data (using the short-lived radionuclide ^{56}Co, half-life = 77 days) with those directly determined with the cosmic-ray detectors on satellites. (Radiochemical data of course refer to the time-integrated fluxes and hence we have to restrict a comparison with satellite data which can provide the time integrals.) An intercomparison of the satellite and the lunar radiochemical data was first made at a conference 'Modern and ancient energetic particles from the Sun' organized by R. M. Walker at the Lunar Science Institute, Houston in September 1971. It was then realized that although the solar flare data were analysed and published by all the four I.M.P. experimenter groups (A.P.L., Bell, G.S.F.C. and Chicago), improvements were desirable in the data analysis and handling procedures. It was then decided that each group would make an attempt to generate particle flux data on suitable time scales and have this information available to all scientific groups through the National Space Science Data Center (Hsieh 1971). An extensive discussion (King 1972) of the I.M.P. data is now available. J. H. King (private communication) has also summarized information on peak fluxes and time integrated fluxes of protons above 10, 30 and 60 MeV for the major cycle – 20 particle events.

Table 3. Radiochemical time averaged lunar and I.M.P.-4 proton spectra for some solar flares during 1969–1971

time period of major flare (Apollo mission number)	radiochemical data: omni-directional (4π) flux of protons of $E \geqslant 10$ MeV / cm^{-2} s^{-1}	radiochemical data: mean characteristic rigidity† / MV	reference	I.M.P.-4 satellite data‡: omni-directional (4π) flux of protons of $E \geqslant 10$ MeV / cm^{-2} s^{-1}	I.M.P.-4 satellite data‡: mean characteristic rigidity / MV
12–17 Apr. 1969 (Apollo 11)	1.7×10^9	(50–150)	S.H.R.E.L.L.D.A.L.F.F. (1970)	1.5×10^9 (2.3×10^9)	50
2–6 Nov. 1969 (Apollo 12)	7.1×10^8	80	Finkel *et al.* (1971)	8.7×10^8 (7.5×10^8)	70
24–29 Jan. 1971 (Apollo 14)	1.0×10^9	100	Wahlen *et al.* (1972)	1.5×10^9 (1.5×10^9)	65

† An exponential rigidity (R) spectrum is assumed for the time averaged spectrum of protons in the flare: $dN/dR = \text{const.} \exp(-R/R_0)$. The hardness of the spectrum is characterized by R_0, the characteristic rigidity.
‡ Two integrated flux values are given. The first one is from King (1972). The second flux value (within parenthesis) and the single value given for R_0 are from Bostrom *et al.* (1967–71).

As can be seen from table 3, there is a reasonably good agreement between I.M.P.-4 and ^{56}Co based on solar proton fluxes and energy spectra, although it does seem that radiochemical R_0 values are generally higher than those based on I.M.P.-4 data.

Long term solar proton fluxes are based on analysis of radionuclides ^{26}Al and ^{53}Mn. The radiochemistry-based data are summarized in table 4 for one rock each from Apollo 12 and 14 missions; in this table, results for the short lived radionuclides ^{22}Na and ^{55}Fe are also tabulated. It becomes quite clear from table 4 that over long or short periods, (few years to a few million years), the time averaged solar flare proton spectrum essentially remains the same; the flux of protons of $E \geqslant 10$ MeV is 80–100 cm^{-2} s^{-1} (4π omni-directional) and $R_0 = 80$–100 MV.

In the case of α-particles, the data available so far on the concentrations of ^{59}Ni (half-life $= 8 \times 10^4$ a) in the Apollo 11 soil sample 10084 and the Apollo 12 rock 12002 indicate a value of 8 α-particles cm^{-2} s^{-1} above 2.5 MeV/nucleon (Lanzerotti *et al.* 1973). More precise experimental data are expected to become available and then it would be possible to deduce an accurate 0.1 Ma time averaged value for the α-particle spectrum.

We have discussed above selected cases of radiochemical studies pertinent to study of solar flare proton and α-particle spectra. For completeness, reference is made to the study of argon isotopes by Fireman, D'amico, De Felice & Spannagel (1972*a*, *b*), of ^{14}C by Begemann, Born,

TABLE 4. TIME INTEGRATED AVERAGE SOLAR COSMIC-RAY PROTON FLUXES (AVERAGED OVER TIME INTERVALS CORRESPONDING TO MEANLIVES OF ISOTOPES) BASED ON RADIOCHEMICAL STUDIES† OF APOLLO 12 AND 14 ROCKS

radio-isotope	mean life a	time averaged omni-directional (4π) flux‡ of protons of $E \geqslant 10$ MeV ($R \geqslant 137$ MV) $cm^{-2}\ s^{-1}$		time averaged characteristic rigidity/MV	
		Apollo rock 12002	Apollo rock 14321	Apollo rock 12002	Apollo rock 14321
^{22}Na	3.75	110	100	85	85
^{55}Fe	3.9	100	100	100	85
^{26}Al	1.1×10^6	80	70	100	95
^{53}Mn	5.3×10^6	90	100	100	100

† Apollo 12 and 14 rock data are from Finkel *et al.* (1971) and Wahlen *et al.* (1972) respectively. In the case of rock 12002, the integrated flux and R_0 values are those recalculated by Wahlen *et al.* (1972).

‡ The radiochemical data were analysed on the assumption that the time averaged solar proton spectra has an exponential rigidity shape: $(dN/dR) = \text{const.} \exp(-R/R_0)$, where R is the proton rigidity and R_0 is the characteristic rigidity. Note that rigidity is expressed in MV. For obtaining particle fluxes in units of $cm^{-2}\ s^{-1}\ sr^{-1}$, divide the omni-directional (activation) flux values in the third and fourth columns by 4π.

Palme & Wanke (1972) and Boeckl (1972) and the non-destructive assay of several radionuclides in Apollo samples by Rancitelli, Perkins, Felix & Wogman (1972) and O'Kelley, Eldridge, Schonfeld & Northcutt (1972).

ANCIENT FLUXES AND ENERGY SPECTRA OF V.H. AND V.V.H. NUCLEI

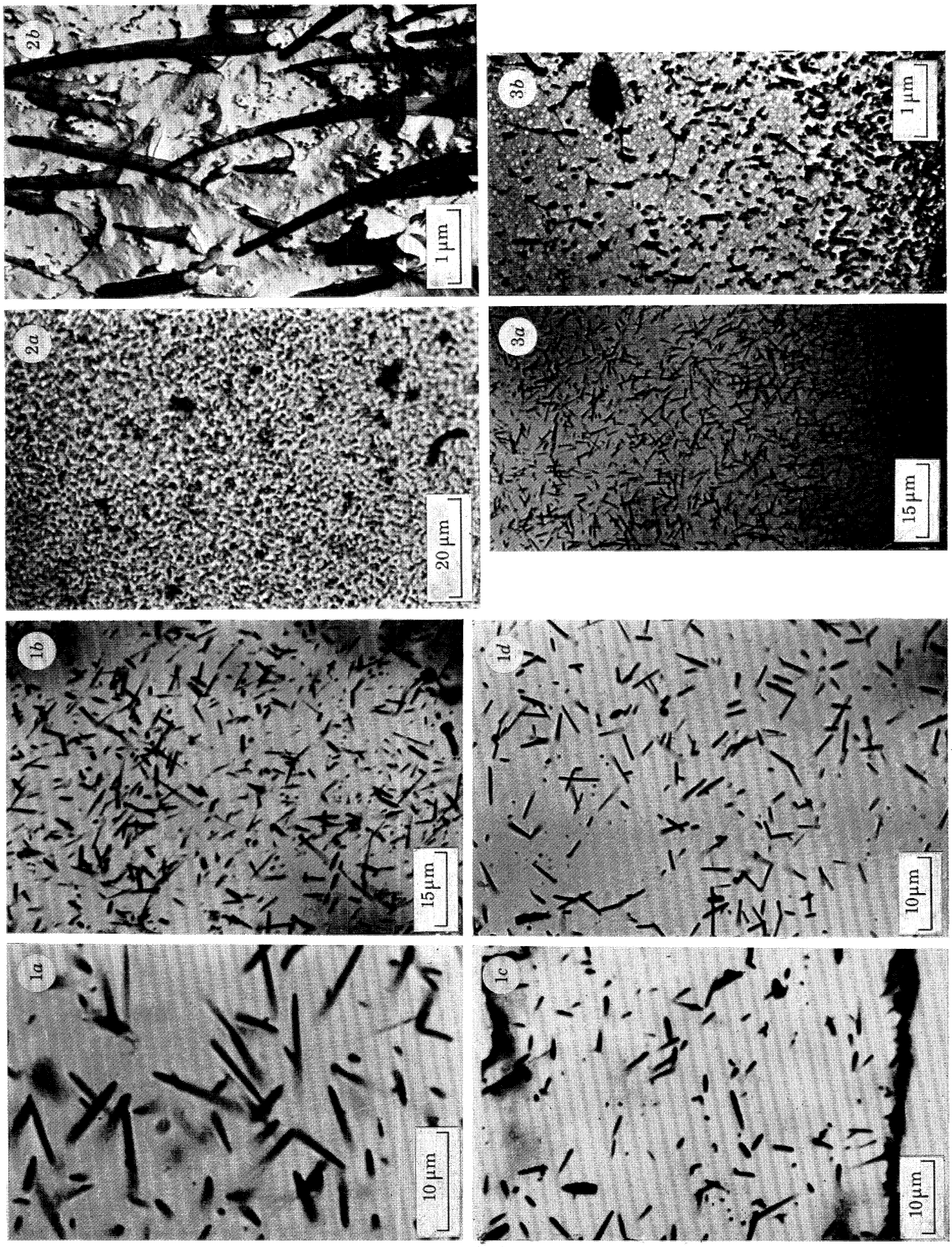
Fossil tracks due to iron group and heavier nuclei were first studied by Fleischer *et al.* (1967*b*). In fact, it may be noted here that the experimental proof for the existence of the v.v.h. nuclei ($Z > 30$) was first provided by these observations for the ancient cosmic radiation, just before P. H. Fowler discovered (Fowler, Adams, Cowen & Kidd 1967) their existence in contemporary cosmic radiation by exposing photographic emulsions at balloon altitude. The realization of the tremendous potential of the fossil track method for studying the prehistory of cosmic-ray radiation led to very concerted efforts by a number of groups in India, Europe, U.S.S.R. and the U.S.A. to improve and extend this technique suitably. These efforts have indeed been very successful as can be seen from the exposé in a recent article (Lal 1972).

DESCRIPTION OF PLATE 14

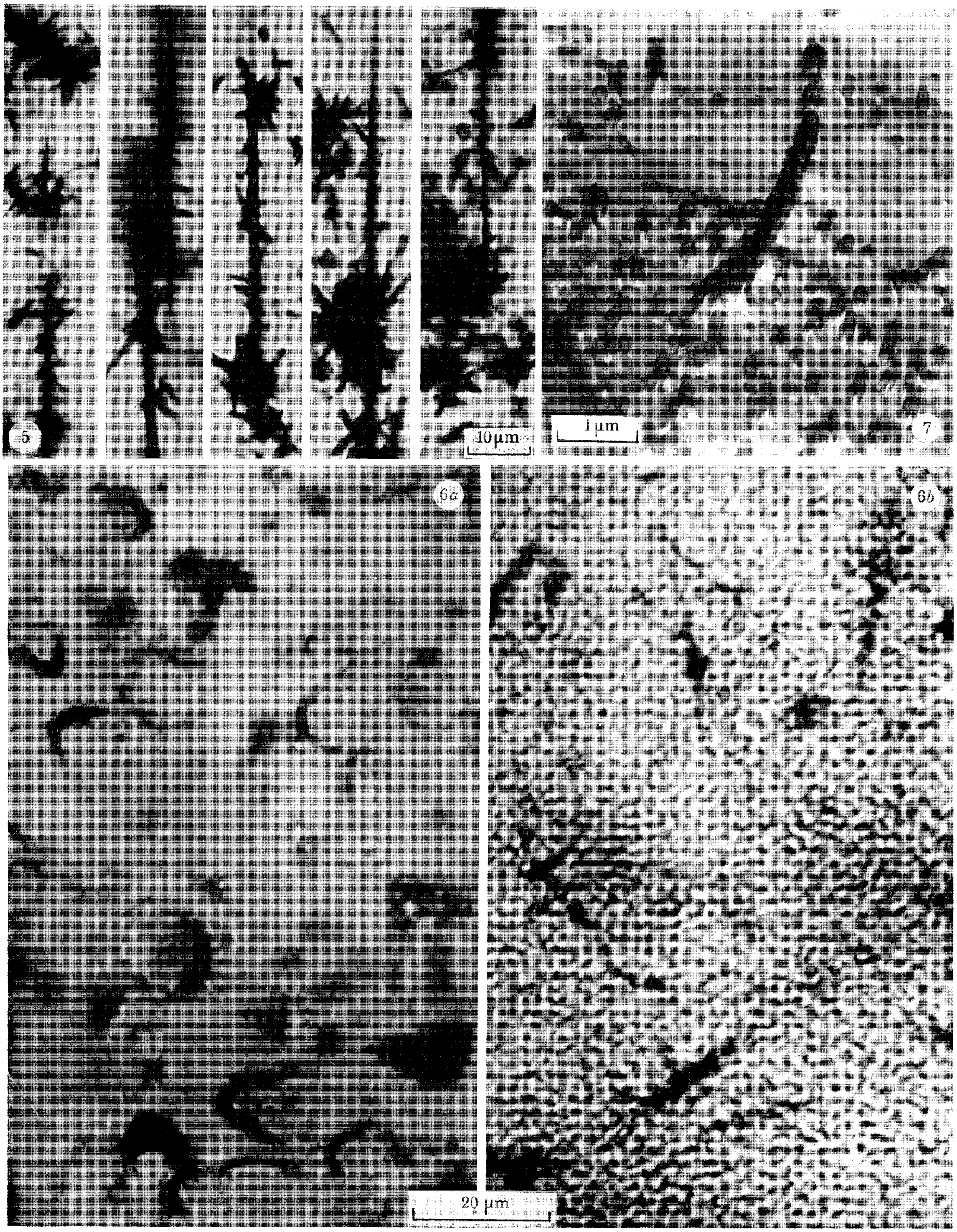
FIGURE 1. Photomicrographs of fossil tracks in *crystals* (mineral grains) from Moon, meteorite and terrestrial samples. (*a*) and (*b*) show tracks due to heavy cosmic-ray nuclei ($Z > 20$) in the meteorites, Moore County and Patwar respectively. (*c*) shows fossil tracks observed in a grain from the lunar soil, 12028, 118. In contrast, tracks in (*d*) are due to fission fragments arising from spontaneous fission of ^{238}U in a terrestrial apatite sample. (Track holes were decorated with silver for increasing optical contrast.)

FIGURE 2. Examples of high fossil track densities ($> 10^8\ cm^{-2}$) due to low energy iron group nuclei of energy below 10 MeV/nucleon, in the lunar samples 10084, 153 (*a*) and 12037, 57 (*b*). At such densities, tracks cannot be resolved with an optical microscope (*a*); it becomes necessary to use electron microscope technology. (*b*) is an electron micrograph taken using the replica technique which was applied for systematic observations of low energy cosmic-ray nuclei by Macdougall *et al.* (1971).

FIGURE 3. Photomicrographs of cosmic-ray tracks in 'irradiated' pryoxene and olivine crystals from the Kapoeta meteorite (*a*) and lunar soil sample 12037, 57 respectively. Note the large gradients in track densities in a direction normal to the crystal edge. Tracks are primarily due to low energy v.h. nuclei.



FIGURES 1–3. For description see opposite.



FIGURES 5–7. For description see opposite.

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

We will not discuss the fossil track technology here in any detail. However, since this is a new technology, we would show as illustrations a few views of the fossil tracks and the type of information which is available by this method.

Photomicrographs of tracks due to iron group and heavier nuclei in meteorites and lunar samples are shown in figure 1, plate 13. Typically, track density values in the range of $(1\text{–}10)\times 10^6$ in meteorites correspond to v.h. nuclei of 200–1000 MeV/nucleon and exposure ages of about 10–50 Ma. In lunar rocks, similar track densities are also seen, but at shallow depths (within 0.1 cm of the surface), track densities are much higher. The highest track densities, of course, exist at the surface. In figures 2 and 3, plate 13, we show examples of high track densities in crystals from Apollo 11 and 12 lunar soil samples. These tracks were stored in (effective) irradiation periods of the order of 10^5 a.

Tracks at depths less than 100 μm ($E < 20$ MeV/nucleon; see table 1) are predominantly of solar flare origin, as we will see later. Record of solar flare irradiation prior to accretion of meteorites is found in certain meteorites (Lal & Rajan 1969; Pellas *et al.* 1969). It is characterized by marked gradients in track densities over distances of the order of micrometres from the surface exposed to low energy particles in space. Examples of such tracks in a meteorite and in a lunar grain are shown in figure 3.

One of the important technological developments in the fossil track field is the thick section technique (see Bhandari *et al.* 1972*b*) which allows precise measurements in gradients and track densities as a function of depth from the outer surface of the sample. A grain from the lunar soil or a chip from the surface of a rock is first embedded in a suitable epoxy resin. Subsequently, the sample is sectioned in orthogonal planes and fossil tracks studied in different mineral grains in the matrix without losing information on the orientation of the sample during its exposure. This technique allows a measurement of gradients in track densities over distances of the order of micrometres. In figure 4, as an illustration, we show how one of the rocks was sectioned from different positions. In the same figure the measured track densities in the same rock are also plotted as a function of depth in the rock.

In the preceding, we have shown photomicrographs of tracks due to low energy (< 20 MeV/nucleon in figures 2 and 3) and higher energy ($\geqslant 200$ MeV/nucleon in figure 1) v.h. nuclei. It should of course be remembered here that the 'recordable' track lengths are only a function of Z and not the initial energy of the particle because the tracks are etchable

---

Description of plate 15

Figure 5. Typical examples of fossil tracks produced by nuclei in the region of $Z = 35\text{–}40$. These tracks were observed in pyroxene and olivine grains of the meteorite Patwar. The short intersecting tracks or track clusters are primarily due to iron group nuclei. For details of this technique of exposing v.v.h. tracks, reference is made to Lal, Rajan & Tamhane (1969). (The track holes were decorated with silver to increase optical contrast.)

Figure 6. In lunar grains, after a mild etching, one often observes dramatic crater and cone-like forms due to solid state damage produced by low energy v.h. and v.v.h. nuclei. The tracks due to v.v.h. nuclei in a background of high track density due to v.h. nuclei can be seen in (*a*): here the mineral grain is olivine (from the lunar soil 12025, 69) which is very suitable for a quantitative study of low energy v.v.h. tracks. In (*b*), the large 'craters' are in fact overetched v.v.h. tracks in a feldspar grain from the lunar soil sample 14151, 14.

Figure 7. Electron micrograph of a replica of fossil tracks revealed in an olivine crystal from lunar soil 15211, 49. The long track standing out in this photograph is due to a low energy (< 10 MeV/nucleon) nucleus of $Z > 30$: the background of short tracks is predominantly due to iron group nuclei.

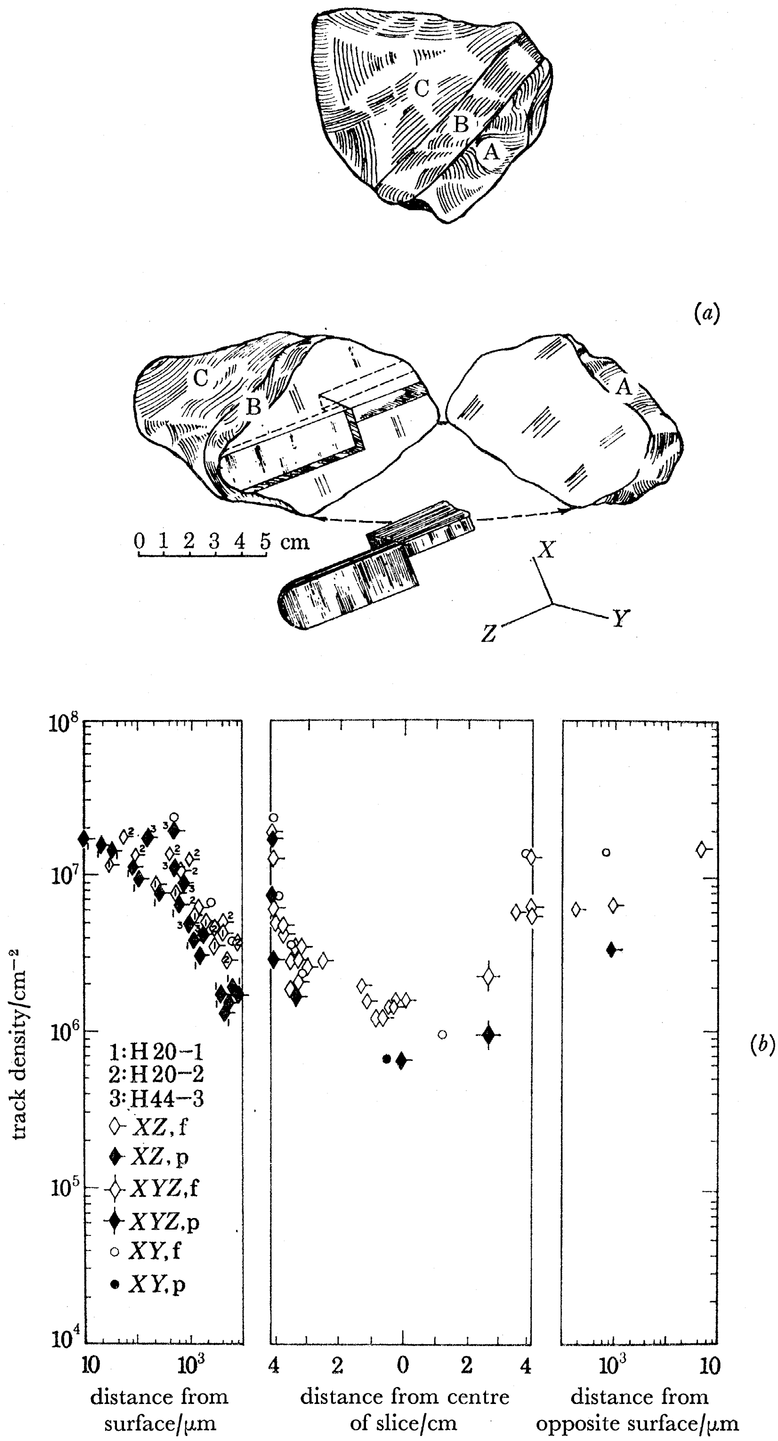


FIGURE 4. Measured fossil track densities (for tracks of length ⩾ 1 μm) based on thick-section studies of the Apollo 12 rock 12018 (*b*); f, feldspar; p, pyroxene. The positions of the samples analysed are shown in (*a*).

over a finite interval of energy, say $(\Delta E)_Z$ between E_1 and E_2 depending on the value of Z and the mineral. The function $(\Delta E)_Z$ is a sensitive increasing function of Z and therefore one expects the recordable track lengths to be larger for the v.v.h. nuclei.

As yet there exists no precise charge calibration of the minerals, but experiments with artificially accelerated ions (Price, Lal, Tamhane & Perelygin 1973) suffice to allow one to study certain broad charge groups. So far, the information on recordable ranges for different ions allows only a study of the broad charge groups, v.h. ($Z \geqslant 20$) and v.v.h. ($Z \geqslant 30$). In future, with a better charge calibration of rock minerals, it should become possible to discuss the relative abundances of multicharged nuclei in narrow width charge groups ($\Delta Z = 3$–5).

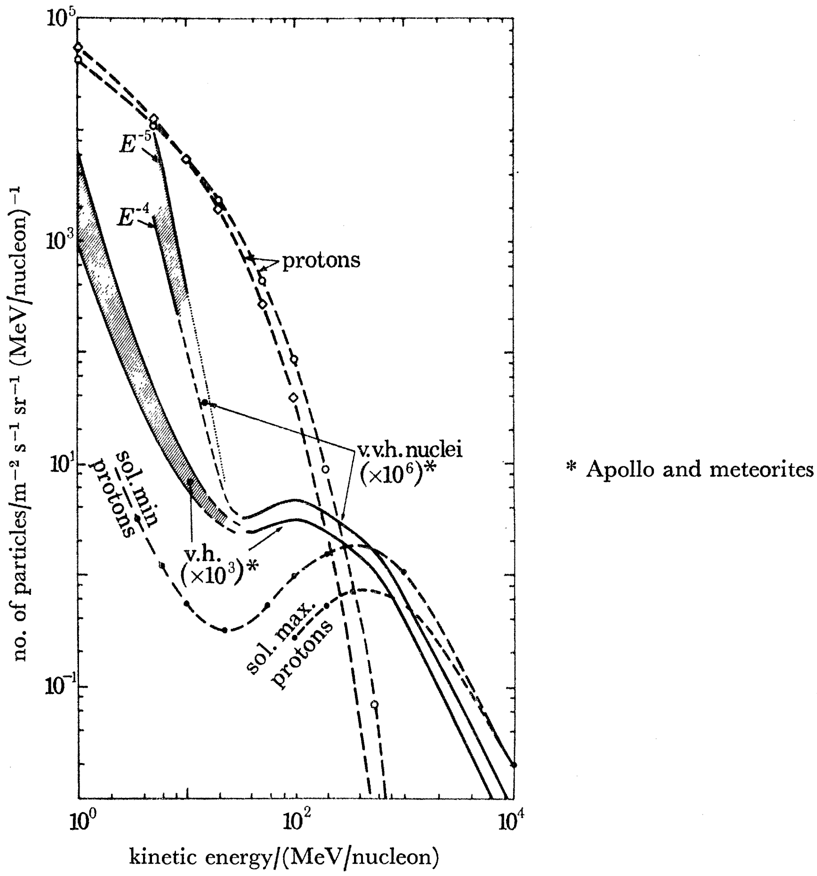


FIGURE 8. Differential kinetic energy spectra of protons, v.h. and v.v.h. nuclei, based on study of cosmogenic effects in lunar rocks and meteorites. The limits for proton fluxes are given by two curves labelled $J\,(4\pi) = 80$ (◇) or, 100 (○) cm^{-2} s^{-1} and $R_0 = 80$ (◇) or 100 (○) MV. In the case of v.v.h. and v.h. spectra, at lower energies, $E < 20$ MeV/nucleon, there exist uncertainties in the calculation of flux in space; the shaded regions show the plausible range in spectral shape and flux values. The recently measured fluxes of galactic cosmic-ray protons (●) during solar minimum and maximum periods (Fan *et al.* 1966) are also shown.

Because of low abundance of v.h. nuclei, it becomes necessary to adopt special techniques to see the 'longer' v.v.h. tracks in the presence of v.h. tracks (Lal 1969). When the v.h. tracks are erased off, one clearly sees the v.v.h. tracks; in figure 5, plate 15, photomicrographs of several v.v.h. tracks due to $Z \geqslant 30$ nuclei of $E > 200$ MeV/nucleon are shown.

Similar to the case of the v.h. nuclei, much larger track densities are usually encountered due to low energy v.v.h. nuclei and high resolution observation techniques became necessary.

Figures 6 and 7, plate 15, show tracks due to low energy ($E < 20$ MeV/nucleon) v.v.h. nuclei in lunar soil grains.

The long term averaged kinetic energy spectra of v.h. and v.v.h. nuclei inferred by Bhandari *et al.* (1971) and Bhandari, Goswami & Lal (1973*b*) are presented in figure 8. (Note that the ranges in the kinetic energy for the spectra deduced for v.h. and v.v.h. nuclei are 1–1500 MeV/nucleon and 5–1500 MeV/nucleon respectively; the extension to higher energies being purely hypothetical.) The results are based on an analyses of about 25 lunar rocks and a few meteorites which were found to have suffered only small ablation in atmospheric transit. For the low energy part of the spectrum, 1–30 MeV, the data on the slope of v.h. spectrum have been deduced by several groups (Bhandari *et al.* 1971; Crozaz, Walker & Woolum 1971; Barber *et al.* 1971). At higher energies, the only relevant results so far, other than those of Bhandari *et al.* (1971, 1973*a*, *b*) are due to Walker & Yuhas (1973) for the kinetic energy interval (50–650) MeV/nucleon, based on the analysis of one lunar rock. For the higher energy interval, no other data exist so far.

Table 5. Temporal and spatial variations of heavy nuclei ($Z \geqslant 20$) abundances in cosmic rays

		$(dN/dE)_{Z \geqslant 30}/(dN/dE)_{Z > 20}$			
		solar†		galactic	
irradiation time interval	distance from Sun/AU	5 MeV/nucleon	10 MeV/nucleon	30–500 MeV/nucleon	500–1000 MeV/nucleon
present – 3 Ma	1	—	—	1.7×10^{-3}	1.7×10^{-3}
present – 1 Ga	1	1.5×10^{-1}	2.5×10^{-2}	1.3×10^{-3}	—
present – 60 Ma	2–3	—	—	1.2×10^{-3}	1.3×10^{-3}
~ 4.5 Ga ago	2–3	—	—	1.4×10^{-3}	—

† The $(Z \geqslant 30)/(Z > 20)$ abundances above 5 and 10 MeV/nucleon are 4×10^{-3} and 1.5×10^{-3} respectively.

The v.v.h. kinetic energy spectrum in figure 8 is based on the measured v.h. spectrum and the relative abundances of v.v.h. and v.h. nuclei in diverse lunar and meteorite samples (Bhandari *et al.* 1973*d*; Bhandari & Padia 1974) exposed for widely different time periods during the last 4.5 Ga. The data on relative abundances of v.v.h./v.h. nuclei for different time periods are summarized in table 5.

Summary of archaic cosmic-ray data

We will now summarize our present-day information on the archaic cosmic fluxes, separately for protons, α-particles and v.h./v.v.h. nuclei.

(*a*) *Protons*

In the case of protons, the two spectra given in figure 8 represent the range of fluxes, within experimental uncertainties, of the low energy part of the spectrum below about 150 MeV – i.e. the solar flare proton spectrum. Deductions on the solar flare proton spectra are based on the assumption that the long term averaged proton spectrum can be well represented by an exponential rigidity type of spectrum: the data on ^{26}Al and ^{53}Mn isotopes which provide time averaged solar proton fluxes back to 1–5 Ma in the past are consistent with the average values of N ($\geqslant$ 10 MeV) = 90 cm^{-2} s^{-1} (4π omni-directional) and R_0 = 90 MV (see table 4).

At energies above 500 MeV, the ancient proton fluxes are deduced to be similar to those at present. For these energies, the radiochemical data have not yet directly led to the delineation of the proton spectrum. The results for Aroos meteorite showed that the cosmic-ray proton fluxes above 500 MeV have essentially remained constant during the last few million years, within 25–50 % (Arnold *et al.* 1961); the experimental and calculated isotope production rates in Aroos for nuclides of half lives ranging from a month to few million years, given in table 6, immediately qualify this statement. Subsequent work by several groups confirmed this result and the measurements of cosmogenic ^{40}K-activity in iron meteorites extended the concept of constancy of cosmic-ray flux in ancient periods back to about 1 Ga (see Lal 1965). The lunar data for protons of $E \geqslant$ 200–300 MeV are also consistent with the results based on analyses of meteorites (Imamura *et al.* 1972; Reedy & Arnold 1972).

Table 6. Cosmic-ray produced radioactive nuclides in the iron meteorite Aroos

nuclide	half-life	observed radio-activity in Aroos† d min^{-1} kg^{-1}	estimated production rate‡ normalized to ^{36}Cl activity	ratio of observed activity to estimated production rate
^{3}H	12.3 a	—	192	—
^{10}Be	1.6×10^{6} a	4.64	4.96	0.935
^{22}Na	2.6 a	2.40	1.76	1.31
^{26}Al	7.3×10^{5} a	4.16	1.6	2.6
^{32}Si	*ca.* 350 a	0.96	0.8	1.2
^{36}Cl	3.1×10^{5} a	(16)	(16)	(1)
^{37}Ar	35 d	20.8	10.4	2.0
^{39}Ar	269 a	15.2	14.4	1.05
^{45}Ca	163 d	4.8	4.48	1.07
^{46}Sc	84 d	33.6	24.0	1.4
^{44}Ti	47 a	4.96	6.08	0.82
^{48}V	16 d	96	116.8	0.825
^{49}V	331 d	192	153.6	1.25
^{51}Cr	28 d	320	304	1.05
^{53}Mn	3.7×10^{6} a	608	528	1.15
^{54}Mn	312 d	544	608	0.89
^{55}Fe	2.7 a	1920	3520	0.545
^{56}Co	78 d	140.8 (56Co + 58Co)	72	—
^{58}Co	71 d		272	—
^{57}Co	271 d	100.4	88	1.14

† Honda & Arnold (1967). ‡ Arnold, Honda & Lal (1961).

(*b*) *α-particles*

As yet we have only estimates for the integrated fluxes of α-particles above 2.5 MeV/nucleon, for the last approximately 10^{5} a, precise ^{59}Ni measurements should in the future allow deductions on solar flare α spectra. The best estimate today is an integral flux of 8 α-particles/cm^{2} s^{1} (4π omni-directional) of $E \geqslant$ 2.5 MeV/nucleon.

(*c*) *v.h. and v.v.h. nuclei*

(i) *Spectral forms of v.h. and v.v.h. nuclei*

At energies below 20 MeV/nucleon, the v.h. and v.v.h. spectra no longer retain the near parallelism observed at higher energies, $E >$ 30 MeV/nucleon (see figure 8). At low energies, the v.v.h. spectrum is much steeper than the v.h. The archaic spectra for v.h. nuclei at energies above 500 MeV/nucleon is identical to that reported for contemporary cosmic radiation (see Lal 1972). Contemporary v.v.h. data are lacking to make this comparison.

(ii) *Fluxes of v.h. and v.v.h. nuclei*

Time-averaged integral fluxes of protons and v.h. nuclei, based on energy spectra in figure 8 are given in figure 9. The v.v.h./v.h. ratios are energy dependent only below 30 MeV/nucleon (table 5).

(*d*) *Relative abundances of* p, *v.h. and v.v.h. nuclei*

The data on α-particles being limited so far, we will only discuss the data for protons, v.h. and v.v.h. nuclei. Since the spectral forms of these nuclei are not always the same, it seems useful to compare the relative abundances in the integral as well as differential fluxes at a given energy. Such a compilation has been made in table 7 where the solar photospheric and universal abundances are also listed.

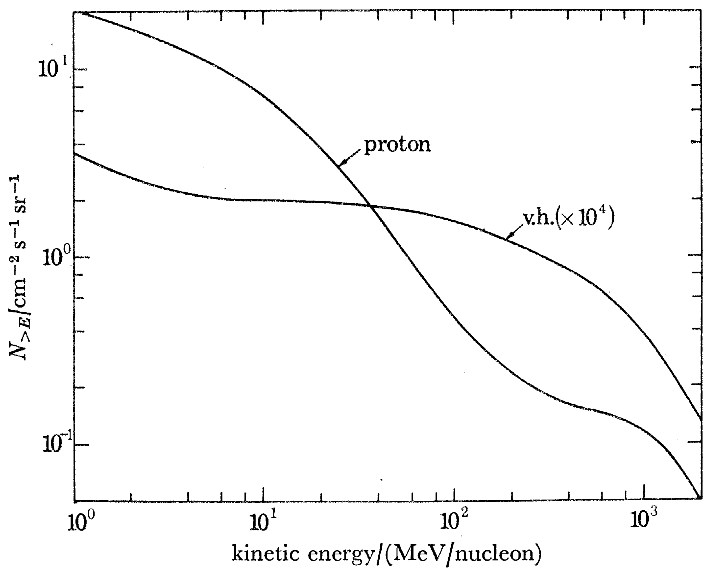


FIGURE 9. Experimentally deduced values of prehistoric integral fluxes of protons and v.h. nuclei, based on radiochemical and fossil track data in the Moon and meteorites. These data are time-averaged over periods of 10^5–10^7 a and are for the 1–3 AU space.

TABLE 7. LONG-TERM AVERAGED RELATIVE ABUNDANCES OF PROTONS, V.H. AND V.V.H. NUCLEI IN COSMIC RAYS

nuclei considered	$(dN/dE)_i/(dN/dE)_j$ kinetic energy/(MeV/nucleon) 5	10	30	relative abundances: solar photosphere†	universal‡
v.h./proton	2.8×10^{-3} (1.9×10^{-5})	1.5×10^{-3} (2.8×10^{-5})	2.5×10^{-3} (8.3×10^{-5})	2.58×10^{-5}	2.68×10^{-5}
v.v.h./v.h.	1.5×10^{-1} (4×10^{-3})	2.5×10^{-2} (1.5×10^{-3})	1.3×10^{-3} (1.3×10^{-3})	1.16×10^{-3}	1.85×10^{-3}

Numbers within brackets refer to ratios of integral fluxes above the energy considered, i.e. $(N \geqslant E)_i/(N \geqslant E)_j$.
† Withbroe (1971).
‡ Cameron (1970).

Concluding remarks on archaic cosmic radiation

The observed spectral shapes of v.h. and v.v.h. nuclei (figure 8) lead one to the following plausible conclusions (Lal 1973; Bhandari *et al.* 1973*a*):

1. At $E \leqslant 10$ MeV/nucleon, both the v.h. and v.v.h. nuclei at 1 AU are of a local origin; from the Sun.
2. At $E \geqslant 10$ MeV/nucleon solar contributions are negligible for v.v.h./v.h. nuclei and one may identify these nuclei as being the galactic cosmic rays. The spectral shapes of v.v.h. and v.h. nuclei are found to be nearly the same for the 25–1500 MeV/nucleon interval. The abundance ratio of $Z \geqslant 30$ to $Z \geqslant 20$ nuclei at these energies is found to be 1.3×10^{-3}, practically independent of time in the past.
3. The observed ratio of differential fluxes of $Z \geqslant 30/Z \geqslant 20$ nuclei at 5 MeV/nucleon is much higher than the ratio in the solar photosphere (Withbroe 1971; Hauge & Engvold 1970). The ratio of total fluxes of v.v.h. and v.h. nuclei in the energy interval 5–10 MeV/nucleon is about 3×10^{-2}, which is more than a magnitude higher value than that for the photosphere: 1.2×10^{-3}.

Studies of solar flare nuclei in the contemporary cosmic rays show that silicon and iron group nuclei are in excess, relative to helium as compared to their abundance in solar corona and photosphere (Price *et al.* 1971, 1973; Price & Sullivan 1972; Lanzerotti 1972; Lanzerotti, Maclennan & Grandedel 1972; Mogro Campero & Simpson 1972; Shirk *et al.* 1973). Archaic data suggest that such an enhancement continues beyond the iron group nuclei and that too even between the closely spaced charge groups – v.v.h. and v.h. nuclei. These observations of course refer to long-term averages and not to an isolated solar flare or two. An explanation of the observed energy dependence of relative abundances of heavy nuclei may rest in the mechanism of acceleration and escape of solar flare particles from the Sun. These processes are not well understood at the present time and all suggestions made so far (Korchak & Syrovatskii 1958; Price *et al.* 1971; Mogro-Campero & Simpson 1972) to explain these enhancements appear to be inadequate.

Two important conclusions follow from discussions in the preceding paragraphs:

1. If a particle detector is exposed in space at 1 AU for long periods of time corresponding to several solar cycles, the time averaged solar and galactic v.h./v.v.h. particle intensities are such that 15–20 MeV/nucleon is the central energy above and below which galactic and solar particles respectively dominate. The corresponding value of the central energy is 200 MeV in the case of protons.
2. The energy spectra of solar v.h. and v.v.h. nuclei are markedly different such that at lower energies, down to 5 MeV/nucleon, the flux of v.v.h. nuclei steadily increases over the v.h. nuclei. The v.v.h./v.h. ratios in the cosmic rays depend so sensitively on the energy region considered and hence it is not meaningful at least at low energies to deduce about stellar compositions from studies of the cosmic radiation. This situation may in fact be expected to prevail for higher energy galactic particles unless their acceleration occurs under very different conditions from those in the Sun. However, the experimental data in table 7 show that at energies above 30 MeV/nucleon, the relative v.v.h./v.h. abundances in cosmic rays and the universal abundances are nearly the same; the v.h. or v.v.h. nuclei are of course enhanced in cosmic rays relative to hydrogen, by about a factor of 3.

A keynote of the archaic data relating to the temporal variations of fluxes or the relative abundances of protons or heavy nuclei is the *constancy*, within a factor of two or less, for the whole range of data summarized here. It may be 'mentioned here' that as far as the solar part of the radiation is concerned, the present data provide information only on the temporal variations in the energy spectra of v.h./v.h.h. nuclei: so far there is no possibility of ascertaining absolute fluxes of the solar nuclei from observations of tracks in lunar soil grains because of lack of an independent method for estimating their exposure ages. However, it is fairly certain that track accumulation at energies below 20–30 MeV/nucleon completely covering the solar part of the radiation, is in an erosion equilibrium. If one then makes the assumption that micro-meteorite flux has not appreciably altered in the past, then one can also state that within reasonable limits the time averaged solar particle fluxes have not varied within a factor of 4 during the last 1 Ga.

The observed constancy in the abundance ratios and spectral shapes of v.v.h. and v.h. nuclei, particularly for the high energy region is probably not surprising although if large variations were observed, it would not be unexpected. At low energies, below 10 MeV/nucleon, the observations simply imply that the solar acceleration processes have not changed during the last few hundred million years. At higher energies, $E \geqslant 30$ MeV/nucleon, the data refer to the galactic cosmic radiation and any variations observed in the 30–500 MeV/nucleon energy region would not have been very surprising considering that these nuclei may in fact largely arise from discrete sources in the vicinity of the Solar System as it travels through different regions of the Galaxy in the last 1 Ga.

The observed constancy in the abundance ratio of v.v.h. and v.h. nuclei is probably in line with the observed extremely low anisotropy of cosmic rays of 10^{11}–10^{12} eV (Elliot, Thambyah-pillai & Peacock 1970), unless these particles are of an extra-galactic origin (Brecher & Burbidge 1972). Lingenfelter, Ramaty & Fisk (1971) have attempted to explain this result as due to the combined effects of one-dimensional diffusion of cosmic rays along the magnetic field lines and the turbulence induced three-dimensional random walk of these field lines. Thus, it is possible to think of complex diffusion models where even such low energy particles are not confined to the vicinity of the source, say within distances of the order of 50–100 pc, the mean distance between two supernovae exploding within time periods of the order of 10^6 a, the central averaging period for the archaic data.

We can clearly anticipate that extension of the work of the type discussed here and refinements of the present technology to include detailed analyses of the chemical composition up to the heaviest nuclei would prove very valuable in understanding about the time variations in the solar activity and provide some ideas regarding the chemical compositions of astrophysical objects responsible for heavy nuclei in cosmic radiation and cosmic-ray propagation mechanisms.

I am grateful to Professor Yash Pal, Professor B. Peters and Dr N. Bhandari for discussions. This work could not have been completed without the scientific help of and discussions with Mr J. N. Goswami.

References (Lal)

Amin, B. S., Lal, D., Lorin, J. C., Pellas, P., Rajan, R. S., Tamhane, A. S. & Venkatavaradan, V. S. 1969 *Meteorite research* (ed. P. M. Millman), Dordrecht: D. Reidel.

Arnold, J. R., Honda, M. & Lal, D. 1961 *J. geophys. Res.* **66**, 3519.

Arrhenius, G., Liang, S., Macdougall, D., Wilkening, L., Bhandari, N., Bhat, S., Lal, D., Rajagopalan, G., Tamhane, A. S. & Venkatavaradan, V. S. 1971 *Geochim. Cosmochim. Acta Supp.* 2, **3**, 2583.

Barber, D. J., Cowsik, R., Hutcheon, I. D., Price, P. B. & Rajan, R. S. 1971 *Geochim. Cosmochim. Acta* **3**, 2705.

Begemann, F., Born, W., Palme, H. & Wanke, H. 1972 Revised Abstracts, Third Lunar Sci. Conf. (ed. C. Watkins), p. 53.

Bhandari, N., Bhat, S. G., Lal, D., Rajagopalan, G., Tamhane, A. S. & Venkatavaradan, V. S. 1971 *Geochim. Cosmochim. Acta* **3**, 2611.

Bhandari, N., Goswami, J. N., Gupta, S. K., Lal, D., Tamhane, A. S. & Venkatavaradan, V. S. 1972*a* *Geochim. Cosmochim. Acta* **3**, 2811.

Bhandari, N., Goswami, J. N., Lal, D., Macdougall, D. & Tamhane, A. S. 1972*b* *Proc. Indian Acad. Sci.* **76**, 27.

Bhandari, N., Goswami, J. N., Lal, D. & Tamhane, A. S. 1973*a* *Proc.* 13*th Int. Conf. on Cosmic Rays, Denver* **2**, 1464.

Bhandari, N., Goswami, J. N. & Lal, D. 1973*b* *Proc.* 13*th Int. Conf. on Cosmic Rays, Denver* **1**, 281.

Bhandari, N., Lal, D. & Tamhane, A. S. 1973*c* *Proc.* 13*th Int. Conf. on Cosmic Rays, Denver* **1**, 287.

Bhandari, N., Goswami, J. N., Lal, D. & Tamhane, A. S. 1973*d* *Astrophys. J.* **185**, 975.

Bhandari, N. & Padia, J. T. 1974 Secular variations in the abundances of heavy nuclei in cosmic rays. Submitted to *Science, N.Y.*

Boeckl, R. S. 1972 *Earth Planet. Sci. Lett.* **16**, 269.

Bostrom, C. O., Williams, D. J., & Arens, J. F. 1967–71 Solar proton monitor experiment in *Solar geophysical data*, Vols. 282–317, ESSA, Boulder, Colorado 1967–1971.

Brecher, K. & Burbidge, G. R. 1972 *Astrophys. J.* **174**, 253.

Cameron, A. G. W. 1973 *Space Sci. Rev.* **15**, 121.

Comstock, G. M. 1972 *The Moon*, I.A.U. Symp. (eds. H. C. Urey & S. K. Runcorn) **47**, 330.

Crozaz, G., Walker, R. & Woolum, D. 1971 *Proc. Second Lunar Sci. Conf.* (ed. A. A. Levinson), *Geochim. Cosmochim. Acta*, Suppl. 2, **3**, 2543.

Crozaz, G., Drozd, R., Hohenberg, C. M., Hoyt, H. P., Ragan, D. & Walker, R. M. 1972 *Geochim. Cosmochim. Acta*, Suppl. 2, **3**, 2917.

Dran, J. C., Durrieu, L., Jouret, C. & Maurette, M. 1970 *Earth Planet. Sci. Lett.* **9**, 391.

Elliot, H., Thambyahpillai, T. & Peacock, D. S. 1970 *Acta Physica Hungar.* **29** (Suppl. 1), 491.

Fan, C. Y., Gloeckler, G. & Simpson, J. A. 1966 *Phys. Rev. Lett.* **17**, 329.

Fichtel, C. E. & McDonald, F. B. 1967 *Ann. Rev. Astron. Astrophys.* **5**, 351.

Finkel, R. C., Arnold, J. R., Imamura, M., Reedy, R. C., Fruchter, J. S., Loosli, H. H., Evans, J. C. & Delany, A. C. 1971 *Geochim. Cosmochim. Acta* **2**, (Suppl. 2), 2917.

Fireman, E. L. 1972*a* *The Apollo* 15 *lunar samples* (eds. J. W. Chamberlain & C. Watkins). Houston: The Lunar Science Institute.

Fireman, E. L., D'amico, J., De Felice, J. & Spannagel, G. 1972*b* Revised Abstracts, *Third Lunar Sci. Conf.* (ed. C. Watkins), p. 262.

Fleischer, R. L., Price, P. B. & Walker, R. M. 1967*a* *Ann. Rev. Nucl. Sci.* **15**, 1.

Fleischer, R. L., Price, P. B., Walker, R. M. & Maurette, M. 1967*b* *J. geophys. Res.* **72**, 335.

Fowler, P. H., Adams, R. A., Cowen, V. G. & Kidd, J. M. 1967 *Proc. R. Soc. Lond.* A **301**, 39.

Geiss, J., Oeschger, H. & Schwarz, M. 1962 *Space Sci. Rev.* **1**, 197.

Hauge, O. & Engvold, O. 1970 Inst. of Theor. Astrophys. 0510, Report No. 31.

Honda, M. & Arnold, J. R. 1967 *Handb. Phys.* **46/2**, 613.

Hoyt, H. P. Jr., Walker, R. M. & Zimmerman, D. W. 1973 Solar flare proton spectrum averaged over the last 5×10^3 years. Laboratory for Space Physics, Washington University, St Louis, Mo. 63130, Preprint SPP-46, June 1973. Proc. Fourth Lunar Sci. Conf.

Hsieh, K. C. 1971 Supporting role of satellite particle detectors to the study of modern and ancient energetic particles from the Sun. Rapporteur paper at the Houston Conf. on Modern and Ancient Energetic Particles from the Sun, Sept. 1971 (Proc. not published).

Imamura, M., Finkel, R. C. & Wahlen, M. 1973 *Earth Planet. Sci. Lett.* **20**, 107.

King, J. H. 1972 Study of mutual consistency of IMP 4 solar proton data. National Space Science Data Center NSSDC-72-14.

Korchak, A. A. & Syrovatskii, S. I. 1958 *Dokaldy Akad. Nauk SSR* **122**, 792.

Lal, D. 1965 *Proc.* 9*th Int. Conf. on Cosmic Rays, London* **1**, 81.

Lal, D. 1969 *Space Sci. Rev.* **9**, 623.

Lal, D. 1972 *Space Sci. Rev.* **14**, 3.

Lal, D. 1973 Cosmic ray archaeology, *Proc.* 13*th Int. Conf. on Cosmic Rays, Denver* **5**, 3322.

Lal, D. & Peters, B. 1967 *Handb. Phys.* **46/2**, Cosmic rays **2**, 551.
Lal, D., Rajan, R. S. & Venkatavaradan, V. S. 1967 *Geochim. Cosmochim. Acta* **31**, 1859.
Lal, D. & Rajan, R. S. 1969 *Nature, Lond.* **223**, 269.
Lal, D., Rajan, R. S. & Tamhane, A. S. 1969 *Nature, Lond.* **221**, 33.
Lanzerotti, L. J. 1972 Proc. Nat. Symposium on Natural and Manmade Radiation Space (ed. E. A. Warman), NASA-TM-2440, 193.
Lanzerotti, L. J., Maclennan, C. G. & Grandedel, T. E. 1972 *Astrophys. J.*, 173.
Lanzerotti, L. J., Reedy, R. C. & Arnold, J. R. 1973 *Science, N.Y.* **179**, 1232.
Lingenfelter, R. E. 1969 *Nature, Lond.* **224**, 1182.
Lingenfelter, R. E., Ramaty, R. & Fisk, L. A. 1971 *Astrophys. Lett.* **8**, 93.
Macdougall, D., Rajan, R. S., Hutcheon, I. D. & Price, P. B. 1973 *Geochim. Cosmochim. Acta* **3**, 2319.
Macdougall, D., Lal, D., Wilkening, L., Bhat, S., Liang, S., Arrhenius, G. & Tamhane, A. S. 1971 *Geochem. J.* **5**, 95.
Mogro-Campero, A. & Simpson, J. A. 1972 *Astrophys. J.* **171**, L 5.
O'Kelley, G. D., Eldridge, J. S., Schonfeld, E. & Northcutt, K. J. 1972 Revised Abstracts, Third Lunar Sci. Conf. 587.
Pellas, P., Poupeau, G., Lorin, J. C., Reeves, H. & Adouze, J. 1969 *Nature, Lond.* **223**, 272.
Price, P. B., Hutcheon, I. A., Cowsik, R. & Barber, D. J. 1971 *Phys. Rev. Lett.* **26**, 916.
Price, P. B. & Sullivan, J. D. 1972 Paper Sol-9, *Proc. 12th Int. Conf. on Cosmic Rays, Hobart*, **1**, 449.
Price, P. B., Lal, D., Tamhane, A. S. & Perelygin, V. P. 1973 *Earth Planet. Sci. Lett.* **19**, 377.
Rancitelli, L. A., Perkins, R. W., Felix, W. D. & Wogman, N. A. 1972 *Geochim. Cosmochim. Acta*, Suppl. 3, **2**, 1681.
Reedy, R. C. & Arnold, J. R. 1972 *J. Geophys. Res.* **77**, 537.
Shirk, E. K., Price, P. B., Kobetich, E. J., Olborne, W. Z., Pinsky, L. S., Eandi, R. D. & Rushing, R. B. 1973 *Phys. Rev.* (in the Press).
S.H.R.E.L.L.D.A.L.F.F. 1970 : Shedlovsky, J. P., Honda, M., Reedy, R. C., Evans, J. C., Lal, D., Lindstrom, R. M., Delany, A. C., Arnold, J. R., Loosli, H. H., Fruchter, J. A. & Finckel, R. C. Proc. Apollo 11 Lunar Sci. Conf. *Geochim. Cosmochim. Acta Suppl.* 1, **2**, 1503.
Wahlen, M., Honda, M., Imamura, M., Fruchter, J. S., Finkel, R. C., Kohl, C. P., Arnold, J. R. & Reedy, R. C. 1972 *Geochim. Cosmochim. Acta*, Suppl. 3, **2**, 1719.
Walker, R. & Yuhas, D. 1973 Cosmic ray track production rates in lunar materials, Preprint, Washington University, Laboratory for Space Physics, St Louis, Mo. 63130.
Withbroe, G. 1971 The Menzel Symposium on Solar Physics, *Atomic spectra and gaseous nebulae* (ed. K. B. Gebbie), N.B.S. Spec. Pub. 353.

Discussion

H. Elliot (*Imperial College London*). Your results show that the intensity of the v.h. nuclei you have examined has remained constant in time. Have you thought of looking for evidence for a large scale lunar magnetic field that may have existed in the past and which could have shielded parts of the lunar surface from particles of lower energy than those you have discussed here?

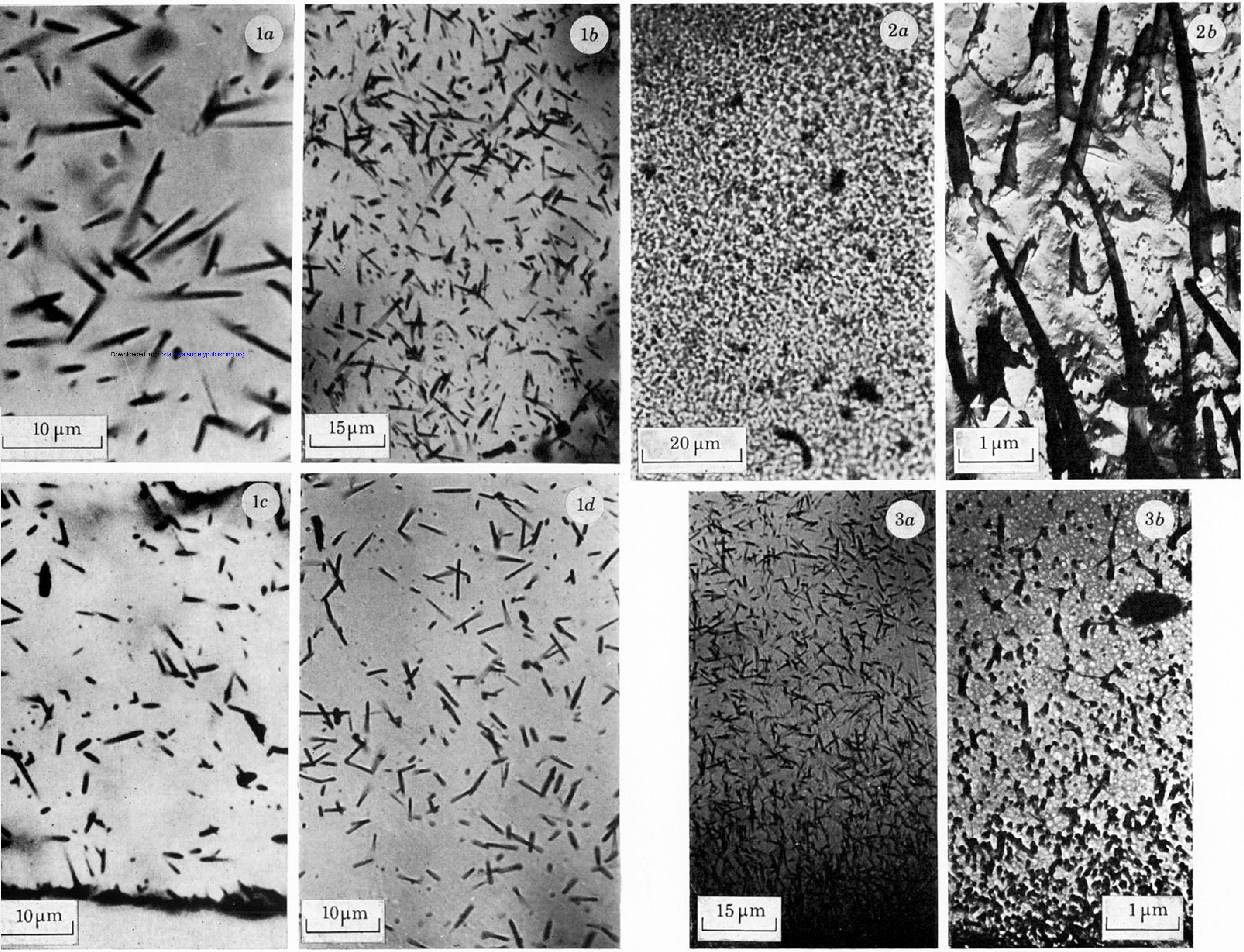
D. Lal. This is a very good suggestion indeed, particularly considering the fact that the remanent magnetization data for lunar rocks does not as yet answer the crucial question whether the Moon ever had a dipole field. The magnetic data only indicate that rocks which solidified $3.2–4 \times 10^9$ years ago were magnetized in a magnetic field of a few microteslas; these fields could be of course of a local origin.

Assuming a dipole lunar field, the calculated values of the field strength at the lunar surface at equator, for a few specified values of the vertical cut-off kinetic energies for iron nuclei (taking into account the 'effective' nuclear charge) are tabulated below:

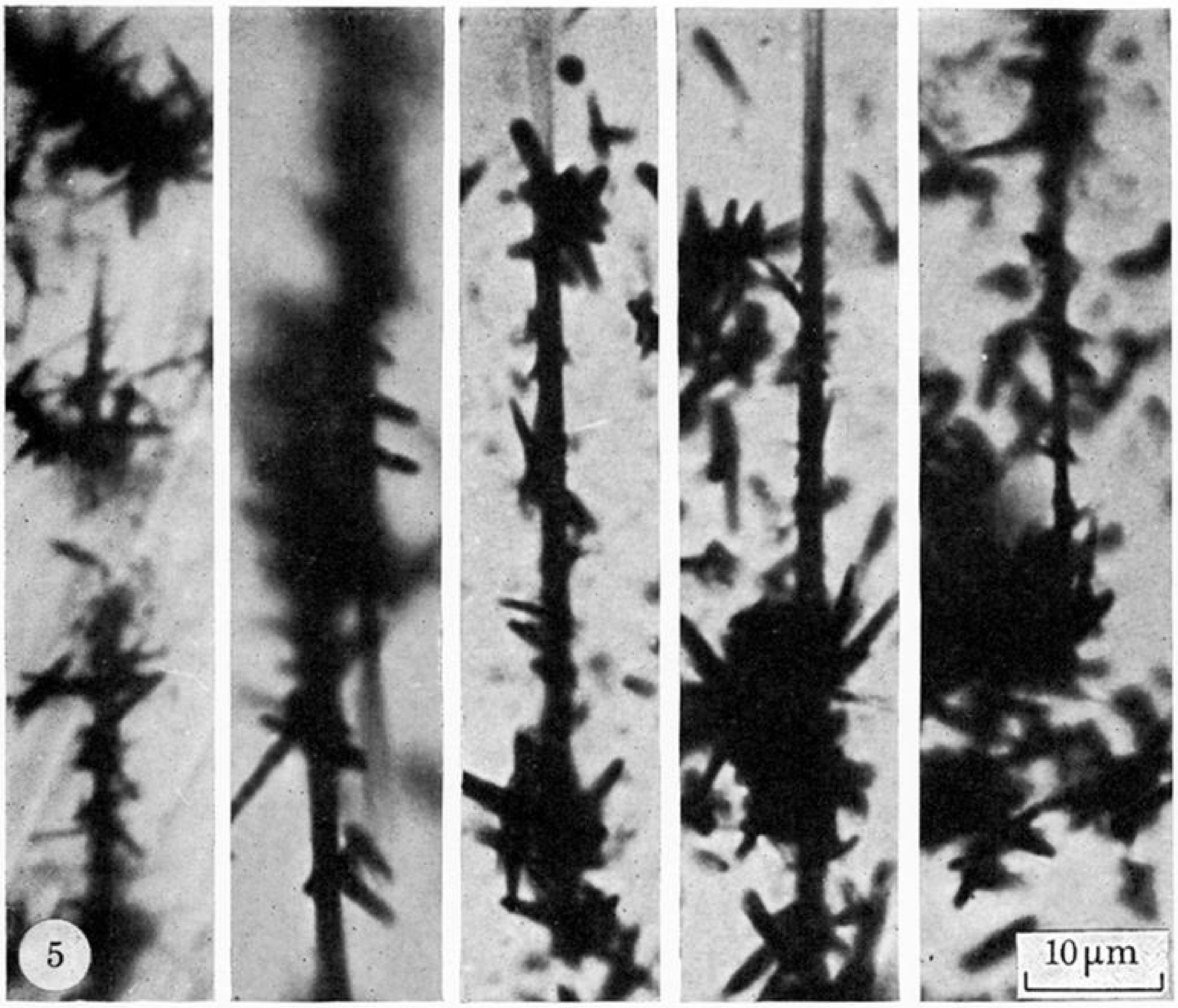
vertical cut-off kinetic energy for iron nuclei at the lunar equator	field strength at the lunar surface
MeV/nucleon	nT
0.1	1150
1.0	1440
5.0	2050

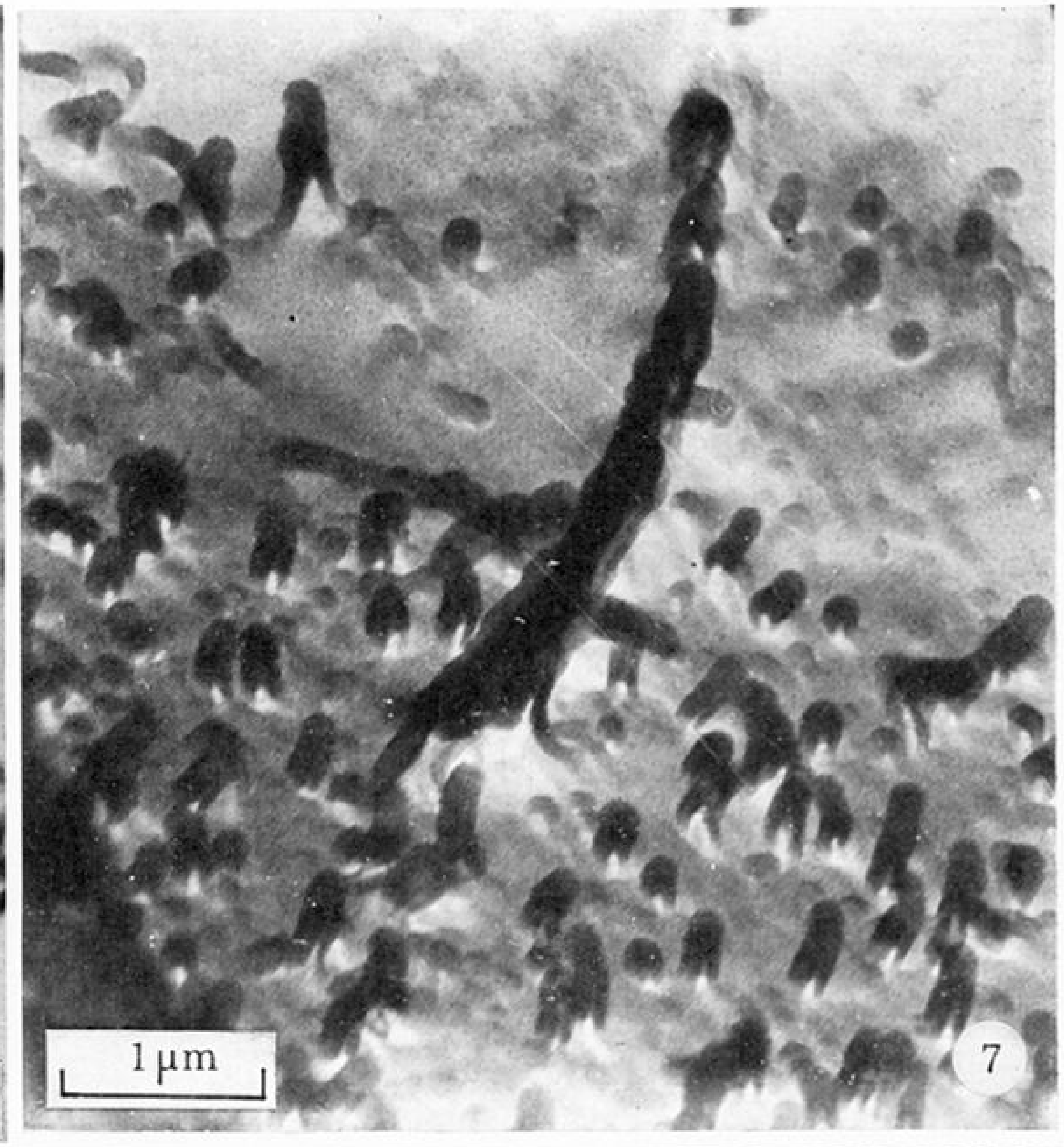
If in the past, iron nuclei of energies below 0.5–1 MeV/nucleon did not reach the lunar equator, this should be clearly manifested by the absence of steep track density gradients within the first 10 μm depth of the samples then exposed at the lunar surface. Thus, if in the past, the Moon had a dipole field exceeding 1 μT, application of the present fossil track technology to 'old' lunar samples where solar flare records are expected to be preserved, should clearly indicate the presence of such magnetic fields. Samples suitable for this study would be the old 'breccia' rocks and grains from great depths in the lunar regolith.

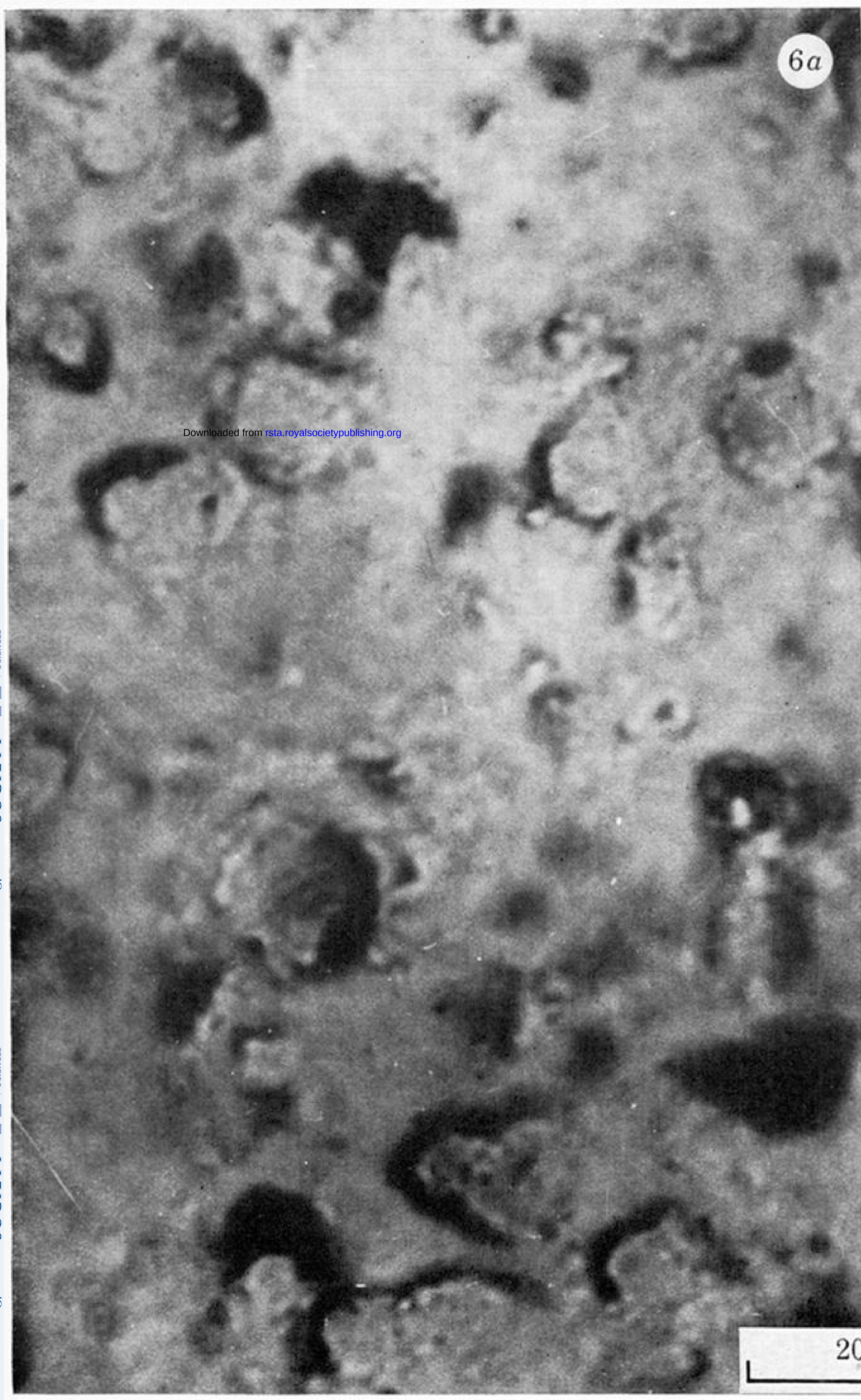
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

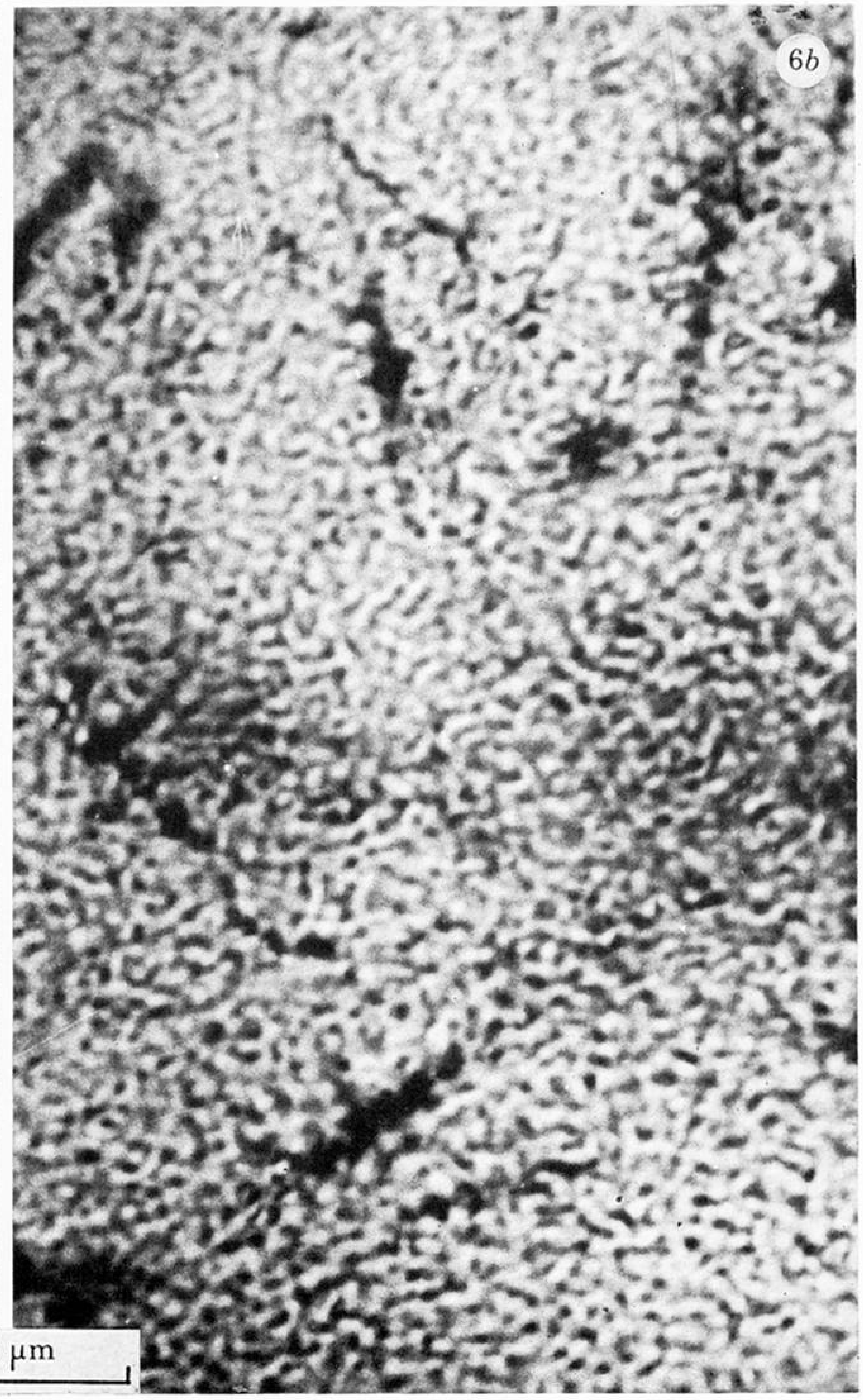


FIGURES 1–3. For description see opposite.









FIGURES 5–7. For description see opposite.