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Phil. Trans. R. Soc. Lond. A 1977 **285**, 309-317
doi: 10.1098/rsta.1977.0070

Phil. Trans. R. Soc. Lond. A. **285**, 309–317 (1977) [309]
Printed in Great Britain

Charged-particle track analysis, thermoluminescence and microcratering studies of lunar samples

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Studies of lunar samples (from both Apollo and Luna missions) have been carried out, using the track analysis and thermoluminescence (t.l.) techniques, with a view to shedding light on the radiation and temperature histories of the Moon. In addition, microcraters in lunar glasses have been studied in order to elucidate the cosmic-dust impact history of the lunar regolith.

In track studies, the topics discussed include the stabilizing effect of the thermal annealing of fossil tracks due to the lunar temperature cycle; the 'radiation annealing' of fresh heavy-ion tracks by large doses of protons (to simulate the effect of lunar radiation-damage on track registration); and correction factors for the anisotropic etching of crystals which are required in reconstructing the exposure history of lunar grains. An abundance ratio of *ca.* $(1.1+0.3)\times 10^{-3}$ has been obtained, by the differential annealing technique, for the nuclei beyond the iron group to those within that group in the cosmic rays incident on the Moon.

The natural t.l. of lunar samples has been used to estimate their effective storage temperature and mean depth below the surface. A suite of samples from known depths in an artificial trench at the Apollo 17 site has been used to calculate the effective thermal conductivity and thermal wavelength of overlying lunar soil at various depths. The temperatures in the shadow of some Apollo 17 boulders, and the duration of the boulders' presence *in situ*, have also been estimated from samples which have been kept refrigerated since their retrieval from the Moon.

Natural and artificially produced microcraters have been studied with the following two main results: The dust-particle flux appears to have fallen off over a certain period of *ca.* 10^4–10^5 years (if the solar activity is assumed to be constant over that interval). Stones predominate in the large (*ca.* 2–10 μm) diameter intervals, while irons outnumber stones at low diameters (*ca.* 1.0 μm), in the micrometeorite flux incident on the Moon.

1. Introduction

Three independent techniques have been used in this laboratory over the last four or five years to study lunar samples – all with broadly the same objective: namely, to elucidate the radiation history of the lunar regolith. The term 'radiation history' is meant to include the record of solar and galactic cosmic rays and of nuclear fission imprinted on lunar glasses and crystals; thermal characteristics of the regolith and the implications of the absorbed energy in the soil; and the effects of cosmic dust particles bombarding the lunar surface.

The three techniques, which have been used as complementary methods in certain overlapping areas of study, are: charged-particle and fission track analysis ('track studies', for short); thermoluminescence (t.l.); and microcratering. Of necessity, only the most salient conclusions of our work to date are reported in this summary review. Fuller accounts of our observations and the bases for our inferences will be found in the references quoted in the sections below, as will the relationship to the conclusions of other lunar workers in these and related fields.

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

2. Track studies

2.1. *Radiation and temperature effects*

Tracks produced in lunar crystals largely by the iron group of nuclei in the primary cosmic rays have been successfully used by us to gauge the effects of lightly ionizing solar-flare particles incident on the lunar surface as well as of the moderately high temperatures (up to *ca.* 400 K) experienced by the lunar regolith. This we have done by comparing the annealing characteristics of fossil tracks in lunar crystals with those of tracks freshly produced in both lunar and analogous terrestrial crystals by accelerated heavy ions of energies ~10 MeV/nucleon on the one hand and of fossil tracks in meteoritic crystals on the other. We find (Bull & Durrani 1975*a*, *b*) that whereas the bulk of fresh Fe-ion tracks in lunar and terrestrial pyroxenes are removed upon subjecting them to *ca.* 500 °C for 1 h, as are fossil tracks in meteoritic enstatites, the fossil tracks in lunar pyroxenes can be eliminated only when they are annealed at *ca.* 600 °C for 1 h.

The inference we draw from these experiments is that the elevated temperatures and high radiation fluxes experienced by the lunar regolith, in contrast to the interiors of meteorites (which are well shielded from low-energy radiations and where typical temperatures are only *ca.* 100–150 K), probably anneal out the peripheral and low ionization-density parts of fossil tracks in lunar crystals. The net effect of such 'seasoning' or 'maturing' processes is that the surviving portion, or the 'core', of the fossil track is hardier and more temperature-resistant than the fresh or unseasoned track. Similar results on the higher resistance of fossil lunar tracks to thermal annealing have been reported by other workers (e.g. Price, Lal, Tamhane & Perelygin 1973). That such seasoning has reduced the fossil tracks to their cores is evident from the maximum etchable lengths attained by fossil versus fresh tracks, using the same etching techniques. Thus, whereas the maximum etchable length of fresh Fe ions (9.6 MeV/nucleon) in pre-annealed lunar pyroxenes and in terrestrial enstatites is *ca.* 25 μm, as measured by the surface polishing method (and *ca.* 12–14 μm by the track-in-track or 'TINT' technique of revelation), that of fossil tracks in lunar pyroxenes from the same sample is found by the TINT technique to be only *ca.* 10–12 μm.

We have, in addition, examined the results of 'radiation annealing' on freshly produced tracks by simulating the effects of lunar radiation-damage on track registration (Durrani *et al.* 1973*a*). The flux of solar-flare protons of energy > 3 MeV is *ca.* 10^{12} cm^{-2} a^{-1} (Haffner 1967), which leads to a total dose of *ca.* 10^{17}–10^{18} protons/cm^2 experienced by lunar grains during their residence in the top surface layers on the Moon. We irradiated soda-lime glass detectors first with 4 MeV/nucleon Fe ions or ^{252}Cf fission fragments (10^4–10^7 tracks/cm^2). They were then subjected to high fluences (10^{14}–10^{17} protons/cm^2) of 3 MeV protons from a cyclotron. The etch-pit diameters resulting from standard etching conditions were carefully measured corresponding to each proton dose.

A systematic reduction in the residual track diameters (accompanied by a fall in the surviving track density) was clearly evident as a function of the proton dose. Thus a proton fluence of 4×10^{16} cm^{-2} resulted in the etch-pit diameters of the Fe ions being reduced to as little as ~15 % of their initial value. A dose of 1.4×10^{17} protons/cm^2 reduced the track density of ^{252}Cf fission fragments by ~50 %. Since the target assembly was kept cool (at ≲ 70 °C) during the proton bombardment, these track annealing effects cannot be attributed to thermal causes. We thus believe that radiation annealing probably plays a similar rôle on the surface of

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

the Moon in leading to smaller but hardier ('seasoned') cosmic-ray tracks as does thermal annealing.

2.2. *Anisotropic etching of tracks*

In attempting to reconstruct the irradiation orientation of lunar grains during their exposure at the very top of the lunar surface (as most grains seem to have experienced at some stage during their regolith-mixing movements), it is important to ensure that no spurious effects enter into track etching procedures. During the course of observation of lunar crystals, we often noticed directional differences in track densities within the same crystal, which could not be attributed to any chemical zonings or track gradients. Systematic experiments were, therefore, carried out (Dorling *et al.* 1974) to detect any anisotropies which were dependent on crystallographic orientations. Our conclusion is that a certain amount of such an anisotropy in the etching behaviour does exist, which varies from one type of crystal to another and also depends on the etching conditions. We have been able to measure appreciable differences in the velocity of etching along different crystallographic axes, which result in the early or late revelation of tracks. Poor etching may, thus, yield different and misleading track-density values in different directions within a crystal; prolonged etching tends to compensate for this artefact.

We have applied such experimentally determined correction factors to the observed track-density profiles in an Apollo 17 feldspar grain in an attempt to infer the unbiased irradiation configuration during its exposure at the very top of the lunar regolith (Durrani *et al.* 1974).

Some differences in the maximum etchable lengths of heavy-ion tracks have also been observed as a function of their orientation with respect to a cleavage plane or the zone lines in a crystal (Bull & Durrani 1975*b*), although more recent observations (Durrani & Bull, unpublished data) have not borne out this conclusion. Preliminary work in this laboratory indicates (P. F. Green, unpublished data) that the annealing characteristics of heavy-ion tracks in mica also depend on the angle of incidence of the ions with respect to the cleavage plane, but that the differences in the case of bronzite crystals, bombarded with Fe, Ni and Kr ions, are negligible. Marked anisotropies have also been observed by us in the annealing behaviour of uranium fossil-fission tracks in apatite crystals. It is, therefore, evident that a more accurate interpretation of the track data, obtained from etching lunar crystals with or without annealing, demands that careful consideration be given to possible crystallographic anisotropies of track revelation.

2.3. *Elemental abundance ratios in cosmic rays*

Lunar crystals are excellent keepers of cosmic-ray track records. A problem often encountered in decoding these records is, in fact, the superabundance of the imprinted information. Track densities of the order of 10^9 cm^{-2} or greater are common. The bulk of these tracks are due to low-energy particles of solar origin which, because of the lunar vacuum and negligible magnetic field, can reach the surface of the Moon relatively unhindered. Differential annealing of charged-particle tracks is a potent technique in this context.

It has been reported by several observers (e.g. Maurette 1970) that tracks due to heavy ions are more resistant to annealing than those of lighter ions. Price, Hutcheon, Lal & Perelygin (1972) proposed that the track-forming particles could be identified on the basis of track-annealing characteristics. Using this approach, we have tried to determine the ratio of the fluence of nuclei beyond the iron group to that within the iron group ($22 \leqslant Z \leqslant 28$) in the cosmic-ray record in lunar crystals. These two groups are usually referred to as the v.v.h. and v.h. components, respectively.

In our study, pyroxene grains from some Apollo 17 samples were subjected to annealing at 590 °C for 1 h, it having been previously established that such an annealing would eliminate all Fe-group tracks. Upon etching the annealed crystals a small number of residual tracks, some of them quite long (> 10 μm), were observed. These tracks are likely to be due either to ions of $Z \gtrsim 28$, or to fission fragments. (The majority of recorded tracks before annealing are due to the Fe-group of particles in solar flares: nuclei of lower charges do not leave etchable tracks in lunar crystals). The uranium content of these crystals was determined by reactor irradiation to be ~ 0.004 ppm. The contribution from the spontaneous fission of ^{238}U and of ^{244}Pu (in the early history of the lunar rocks), as well as from the thermal-neutron induced fission of the ^{235}U content, was estimated to be $\lesssim 10\,\%$ of the putative v.v.h. group.

Another, and more important, correction to the observed v.v.h./v.h. ratio stems from the fact that the energy required to reach a crystal surface at a depth d below the lunar surface is different for particles of different mass and charge. Hence at any given level below the surface the v.v.h. and v.h. fluxes observed relate to different portions of their respective energy spectra; and the form of the solar-flare energy-dependent intensity for both types of particles is $\mathrm{d}N/\mathrm{d}E = kE^{-3}$ (Fleischer, Hart & Comstock 1971). The exact depth of our lunar samples is not known, but the observed track densities (1–3×10^8 cm^{-2}), combined with an absence of significant track-density gradients, suggest an exposure at depths between ~ 100 and 1000 μm from the top surface of the Moon. We have therefore calculated correction terms based on the range-energy relations of Northcliffe & Schilling (1970) for Fe and Ag ions (the latter being taken as a typical v.v.h. ion).

On applying the above corrections to the observed value of $(9 \pm 1.4) \times 10^{-4}$, we obtain the abundance ratio of v.v.h./v.h. components recorded in lunar pyroxenes as $\sim (1.1 \pm 0.3) \times 10^{-3}$, where the large spread is mainly due to the uncertainty in sample depth. This ratio relates to solar-flare particles in the range *ca.* 10–100 MeV/nucleon, and is comparable to that reported by Bhandari & Padia (1974), namely $(1.3 \pm 0.6) \times 10^{-3}$ for ions of ~ 20 MeV/nucleon in lunar olivine grains.

3. Thermoluminescence studies

3.1. *Thermal properties of the lunar regolith*

Part of the radiation energy received by the lunar rocks causes charge carriers (mostly electrons) to get 'trapped' in metastable states in crystals. If the traps are sufficiently stable (having large depth E, and small 'frequency factor' s for the carriers), the energy remains locked for geologically long time-periods until released in the form of thermoluminescence (t.l.) upon the heating of the crystalline grains. Cosmic rays (including those of solar origin) provide the largest radiation dose, namely ~ 10 rad a^{-1} (Haffner 1967), on the lunar surface. The traps are, of course, continually drained by the diurnal temperature wave experienced by the lunar material at any given position in the regolith.

The amount of natural or 'equilibrium' t.l. retained by a sample as a result of these competing processes of radiation-filling and thermal-draining of the traps is, thus, a measure of the effective storage temperature of the sample on the lunar surface, provided that the relevant parameters of the traps concerned can be determined experimentally. Using such procedures, we have estimated the effective storage temperatures, T_{eff}, of a number of fines and 'rock chip' (breccia) samples from Apollo 12, 14, 15 and 16 missions (Durrani *et al.* 1972*a*, *b*, 1973*b*). An example of such determinations is the value of $T_{eff} \approx 372 \pm 5$ for 'comprehensive' (i.e. top 1 cm) fines 14259,78, and $\approx 355 \pm 10$ for the brecciated 'rock chip' 14321,147.

In these calculations, the 'effective' storage temperature takes into account the cyclical variations of the lunar temperature T over a lunation. Since the temperature enters the equations through the exponential factor, its effect on the mean-life τ of a trap is very sensitive:

$$\tau(T) = s^{-1}\, e^{E/kT}, \qquad (1)$$

where k is Boltzmann's constant. For simplicity, we have assumed a sinusoidally varying temperature wave, with an amplitude of ± 150 K at the lunar surface, superimposed on an equilibrium temperature of 240 K. The 'effective' temperature T_{eff} then corresponds to the average value of the Boltzmann factor $\exp(-E/kT)$ over a lunation.

The diurnal heat wave is attenuated very sharply with depth below the lunar surface because of the poor conductivity of the lunar regolith. The calculated value of T_{eff} can, thus, be used to estimate the effective depth of a lunar sample fairly accurately. Using a value of $\lambda \approx 24$ cm for the thermal wavelength in lunar surface fines (Hoyt *et al.* 1970), and an average value of $\lambda \approx 70$ cm for the top 2 m of the lunar regolith, based on the lunar heat probe experiment of Langseth, Chute & Keihm (1973), we have estimated the mean depth of the above-mentioned Apollo 14 fines and rock samples as *ca.* 0–0.1 cm, and *ca.* 1.4(± 1) cm, respectively (Durrani *et al.* 1973*b*).

Table 1. Effective lunar storage temperature T_{eff}, mean thermal wavelength $\bar{\lambda}$, and effective thermal conductivity K of overlying lunar soil above mean depth $\bar{d}$ (assuming a dose rate of 10 rad/a)

sample†	T_{eff} / K	sample depth, $\bar{d}$‡ / cm	$\bar{\lambda}$ / cm	K / W cm^{-1} K^{-1}
78481,20	360 ± 5	0.5–1.0	52	6.7×10^{-5}
78461,6	359 ± 10	1–6	224	1.4×10^{-3}
78442,1	351 ± 5	6–15	414	5.4×10^{-3}
78421,22	318 ± 5	15–25	255	2.3×10^{-3}
72501,49	365 ± 10	0–4	226	1.4×10^{-3}
Luna 2015	294 ± 5	28–32	225	2.0×10^{-3}

† The first four samples come from the wall of an artificial trench at the base of Sculptured Hills at station 8 (Apollo 17 landing site) in an area of initially undisturbed soil. The fifth sample is from the upper 4 cm of a steep uphill slope at station 2 (about 11 km away from station 8), and is believed to be representative surface material of the South Massif. The last sample comes from the deep drill-core of the Soviet unmanned mission, Luna 20, which landed in a mountainous region in the area of the Apollonius crater.

‡ In calculating $\bar{\lambda}$ and K, the mean, $\bar{d}$, of the depth range shown for each sample has been used.

An interesting application of the above approach has been to reverse the calculations and, from known depths of a series of lunar samples, to derive the thermal wavelength and thermal conductivity values for the lunar regolith after having calculated the effective temperature of the samples at each depth, based on their natural t.l. and trap-parameter measurements. This was done for a suite of four samples collected from known depths within a trench excavated by the astronauts at station 8 of the Apollo 17 mission. Table 1 shows the results of these calculations for the four trench samples as well as one from station 2 (Apollo 17) and one from the Luna 20 deep drill-core. Since the exact depths of the trench samples are not well-documented (they came from a certain range of depths in each case), the values of λ and K are the effective mean values and have considerable uncertainties in them. On applying various corrections (see Durrani & Hwang 1974 for a detailed discussion), however, our mean values of thermal conductivity are found to be in reasonable agreement with those of Keihm & Langseth (1973).

The effective storage temperatures obtained by us shed light on the thermal history of the lunar samples over the last $\sim 10^4$–10^5 a, which is the time required for the equilibrium doses to be accumulated by them (i.e. times of the order of a few mean-lives of the traps concerned). The values of the temperature obtained by us are not very different from those prevalent on the Moon now. This leads to the interesting speculation that, taking the constancy of lunar temperatures over this period as a guide, the glaciation cycles of the Earth during the last 100000 years cannot be attributed to sustained increases in solar heat output leading to enhanced cloud formation and precipitation of snow near the poles. Other causes (e.g. the 'green-house effect' of a CO_2 curtain) must, therefore, be invoked to explain the glaciation pattern on the Earth. Of course, the existence of periods of low solar heat output in the past cannot be excluded on the above evidence.

3.2. *Temperature in the shade*

Because of the vacuum conditions on the Moon, and the loosely packed and hence very poorly conducting surface soil, a striking difference is expected to exist between the temperatures in the sun and in the shade on the lunar surface. Such differences in temperature should show up in the amount of t.l. preserved in the sunlit as against the shaded lunar samples. We have examined some Apollo 17 samples which had been especially requested by us for such a purpose. They included samples collected from the shadows of certain boulders at stations 6 and 2 of the Apollo 17 landing site, as well as surface-soil samples taken from just outside the shadows.

One essential requirement of this investigation was to ensure that the low-temperature parts of the t.l. glow from the shaded samples are not lost during their storage (often lasting several months) in the N.A.S.A. Lunar Receiving Laboratory before their experimental readout. To preserve the t.l. information pertaining to the preceding $\sim 10^4$–10^5 years of storage in the lunar shade (this being approximately the mean-life of the relevant traps in that environment), N.A.S.A. made a special provision at our recommendation (Durrani 1972) to keep the shaded samples in a freezer (at a temperature of *ca.* -20 °C) until their release to us. The samples have, since then, been stored at the liquid-nitrogen or dry-ice temperatures by us throughout the present investigation.

The results of these experiments are very interesting, and their essential features are shown in figure 1. It is clear from the figure that the shaded sample (curve A) not only exhibits a much larger amount of natural t.l. than a similar sample from the adjacent sunlit area (curve B), but the low-temperature glow in the shaded sample (starting at *ca.* 100 °C of readout) is much more effectively preserved than in the sunlit sample. The analysis of the t.l. output is not yet complete, but preliminary calculations indicate (Hwang & Durrani 1975) that the effective temperature of storage in the shadow of the boulder was *ca.* 272 K, as against the sunlit temperature of *ca.* 370 K. More recent experiments (Durrani *et al.*, unpublished data) indicate a temperature of *ca.* 256 K in the lunar shade.

There is some evidence that the boulder concerned, namely number 4 at station 6 (which is 'a sampling site for material which had been mass wasted from the North Massif' in the Apollo 17 landing area, according to N.A.S.A. documentation) had been slowly sliding down hill. This had been inferred by the astronauts from the 'freshness' of the boulder tracks. Our preliminary calculations indicate that the boulder had been *in situ* for a minimum of *ca.* 4×10^4 a, which is approximately the time required for the t.l. in the relevant part of the glow output to reach a steady-state value in the prevailing radiation and temperature environment in the shade. In our more recent work, by analysing the growth characteristics of the natural t.l. induced at 256 K in different readout intervals of the shaded sample, and by applying semi-empirical corrections for 'anomalous fading' of t.l. (since sample collection) in the corresponding parts of the glow curve, we have obtained 6.5×10^4 years as the best estimate for the duration of the boulder shadow.

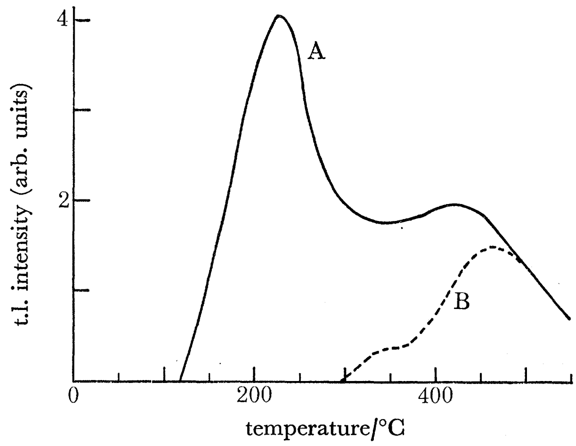

FIGURE 1. Comparison of the natural t.l. glow from a shaded and an unshaded sample. Curve A represents the t.l. from sample 76240,22, which came from *ca.* 1 m inside the permanent shadow of Boulder 4 of the North Massif at the Apollo 17 landing site. Curve B is for sample 76261,25, collected from just outside the shadow. Note the much larger amount of t.l. preserved in the shadowed sample, and also the much lower readout temperature at which the t.l. emission starts from this sample. The shadowed sample has been kept refrigerated ever since its return to the Earth.

4. Microcratering studies

4.1. *Nature and intensity of cosmic-dust incidence*

The lack of an atmosphere on the Moon makes it an ideal place to look for the imprints left by interplanetary dust particles, which are able to reach its surface unhindered. The knowledge of the location and orientation of its impacted rocks makes the Moon superior to meteorites in this respect.

In trying to determine the nature and energy of the impacting particles, we have carried out simulation studies using a dust accelerator capable of electrostatically accelerating micro-projectiles of iron, aluminium, etc., to velocities of *ca.* 1–7 km s^{-1}. These projectiles, typically ranging from *ca.* 0.1 to 5 μm, were made to impinge upon targets of fused silica, soda-lime glass, and tektite glass as well as lunar glass spherules themselves. The main parameters used in these comparative studies are the crater depth-to-diameter ratio χ, and the crater to projectile diameter ratio η.

Information on the time-dependence of the intensity of cosmic dust and micrometeorites incident on the lunar surface has been obtained by reference to the corresponding charged-particle track record. In this study the solar-flare charged-particle tracks, found on the same lunar grains as the ones in which the microcraters are being counted, are used as indicators of the time for which the grains in question have been exposed at the very top surface of the Moon.

In the following paragraphs we summarize the salient results obtained by us from these studies; details may be found in Durrani *et al.* (1974) and other references listed therein.

(1) The size distribution of natural microcraters shows a gradual decrease in the frequency of occurrence with increasing crater diameter. Thus, in 81 light-brown glass spherules of diameters *ca.* 300–350 μm from the Apollo 15 fines sample 15301,84, we found $\sim 8 \times 10^3$ craters/cm^2 with diameter < 1.0 μm, and $\sim 2.8 \times 10^3$ craters/cm^2 with diameter $\gtrsim 1.0$ μm.

(2) The depth-to-diameter ratios, χ, for natural microcraters cluster around three fairly distinct values: 0.31, 0.53 and 0.95, thus suggesting that there are probably three dominant types of micrometre-sized dust particles incident on the Moon. By comparing these values with those for our artificially produced craters, we infer that these three groups correspond, respectively, to (i) very light elements, (ii) Al or Si, and (iii) Fe. While groups (ii) and (iii) obviously suggest stony and iron meteorites, respectively, it is interesting to speculate whether group (i) corresponds to 'ice' micrometeorites (or cometary particles).

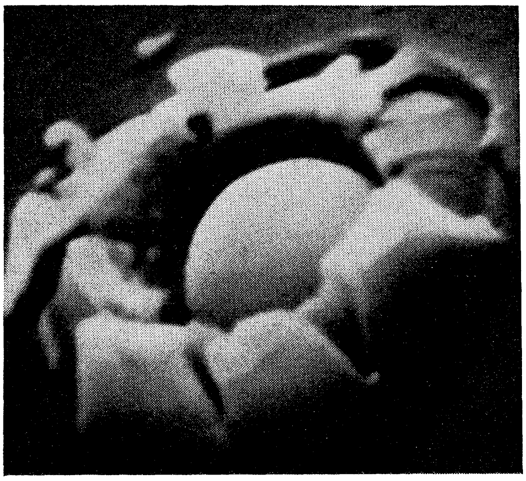

FIGURE 2. During the studies of natural microcraters on light-brown glasses in the Apollo 15 sample 15301,84, a projectile sitting in its crater was observed. (Similar events have been found in simulation experiments with iron microprojectiles.) A microprobe analysis has shown that the natural projectile is mainly composed of iron; the absence of tracks under the crater points to its recent arrival on the Moon.

(3) A comparison of the differential fluxes of micrometeorites (in discrete particle-diameter intervals) indicates that stones predominate in large diameter intervals (*ca.* 2–10 μm), while at low diameters (*ca.* 1.0 μm) iron micrometeorites outnumber the stones. This is consistent with the hypothesis that, in the extremely small size-range, the stones have been selectively driven out of the solar system by radiation pressure owing to their lower specific gravity, since, for the same cross-sectional areas, the stones would be much lighter than irons.

(4) A plot of crater density against track density in lunar glass spherules shows a positive correlation between the two observables. The gradient of the curve representing the crater density as a function of the track density (and hence of the time-period of exposure) appears, however, to be less steep in the nearer past (i.e. in the low track-density region). This would indicate that, assuming the solar-flare flux to have remained constant over the entire time-period recorded on these spherules, the dust-particle flux on the lunar surface has gone down in more recent times, *vis-à-vis* that in the earlier times, over an interval of $\sim 3 \times 10^4$–10^5 a. Since the spherules come from lunar fines, rather than from a fixed lunar rock, and have therefore undergone soil-mixing cycles, the above exposure ages are 'floating periods', i.e. is is not

certain to which historical epoch they belong (though the most recent past is a plausible assumption). Our results are opposite to those of Hartung & Storzer (1974), which indicate an increase in the impact rate over the last *ca.* 10^4 a B.P. The best conclusion may, thus, be to assume that such short-term fluctuations in dust fluxes (or, alternatively, in solar-flare fluxes) even out over long periods of time.

Finally, we show, in figure 2, a rather rare natural phenomenon. The figure shows a natural projectile still sitting in its crater, which was observed on an Apollo 15 light-brown glass spherule. That the phenomenon is not kinematically implausible was demonstrated by similar examples seen in our simulation experiments, where iron projectiles were made to impinge on soda-lime glass. Indeed, in one instance, two captured artificial projectiles were found in the same field of view under a scanning electron microscope. An electron microprobe analysis showed that the natural projectile in figure 2 was composed mainly of iron. One possible mode in which the natural microprojectile could have been captured, rather than bouncing back or evaporating on impact, is through the following sequence: first a larger iron missile melted the lunar rock and turned it into glass; a shower of the evaporated iron then fell back on to the glass spherules while they were still soft, and thus got captured. Further tests on the crater in figure 2 showed a melted base with almost no charged-particle tracks in it. We therefore conclude that the captured particle is probably an extralunar iron micrometeorite which had only recently arrived on the surface of the Moon.

The author wishes to thank all the members of his investigating team for their cooperation; N.A.S.A. and the Royal Society (and through it the U.S.S.R. Academy of Sciences) for the provision of lunar samples; and the Science Research Council for its financial support.

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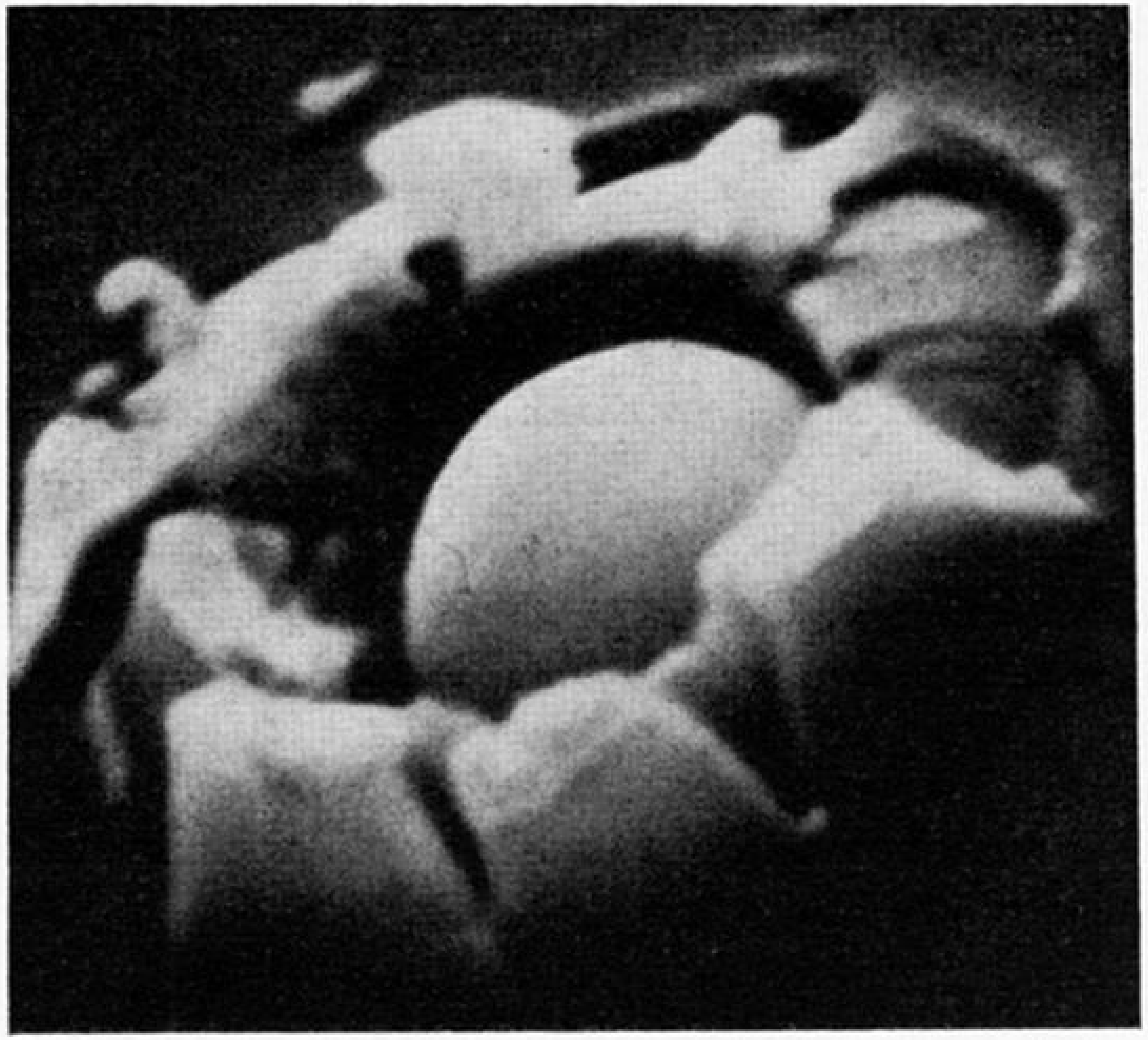

FIGURE 2. During the studies of natural microcraters on light-brown glasses in the Apollo 15 sample 15301,84, a projectile sitting in its crater was observed. (Similar events have been found in simulation experiments with iron microprojectiles.) A microprobe analysis has shown that the natural projectile is mainly composed of iron; the absence of tracks under the crater points to its recent arrival on the Moon.