THE SIMULATION OF LUNAR MICROMETEORITE IMPACTS BY LASER PULSES

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(Received 16 February, 1973)

Abstract. Laser pulses of a finely focused beam were used to simulate micrometeorite impacts on lunar rocks and in lunar soil. The electron microscope pictures show the detailed effects so caused; it is possible to derive an estimate of the comparative amounts of erosion a given micrometeorite flux would cause in lunar rocks and lunar soil.

1. Purpose of Simulation Experiments

While the Moon may have been exposed to a variety of effects that have shaped its surface that are not known or understood, there is little question that high velocity impacts have been a major factor. The large impacts have created the mare basins and the craters, while small meteorites must be eroding rocks and causing some turnover of the lunar soil.

Many microscopic holes have been seen in lunar rocks, and these have been recognized as micrometeorite impact craters. In addition the observation of nuclear effects of cosmic rays a short distance below the surface of lunar rocks has made it possible to estimate the rate at which material has been removed; without such removal the effects would be at saturation level, but in the presence of a certain cosmic ray bombardment rate and a certain material erosion rate, a lower density of the effect is established. Therefore, if we know the cosmic ray bombardment rate, the observations give a measure of the material removal rate from solid rocks, attributed primarily to micrometeorites.

The rate of turning over and mixing of the soil is not directly measurable. If the relation between meteorite cratering in rock and in soil is known, then the rock information can be used to infer about this aspect of the history of the soil.

This investigation has assumed particular importance in view of the observation of distinctive layers in the soil, suggesting that a sedimentation process takes place on the Moon that acts faster than the mixing caused by micrometeorites. Any information about the mixing rate is therefore also information about the unknown surface transportation process.

The simulation in the laboratory of hypervelocity micrometeorite impacts is difficult and expensive. The only method known is to accelerate the micron sized particles by giving them an electric charge and allowing them to fall through a large electric field. Even then the velocities achieved are not as high as those that most commonly occur in meteorite impacts.

If the impact velocity is very high, then the chief effects are due to the energy

The Moon **6** (1973) 405–413. *All Rights Reserved*

instantaneously deposited in a small volume. If this energy per unit is very large compared with that required for evaporation, then even the momentum exchange must be dominated by the recoil of the evaporating material rather than the incoming meteorite momentum. Thus a rock meteorite hitting a similar rock at a high speed would distribute its kinetic energy in a volume two or three times its own (as in the hypersonic flow approximation); if this material is thereby heated far above evaporation temperature, it will instantly evaporate and cause a momentum interchange (recoil) given by the product of mass and velocity of the evaporating material. Thus, if this evaporating material has, for example, three times the mass of the incoming one, the recoil momentum caused would exceed the incoming one by the factor $\sqrt{3}$. Therefore, if one simulated the impact by a sudden deposition of energy without any significant incoming momentum, the total momentum balance will be insufficient, for the same energy deposited, by the factor $(1+\sqrt{3})/\sqrt{3}$ or 1.6. While this is a significant factor, it is not one that can be expected to change greatly the nature of the process or the order of magnitude of any of the measurable quantities resulting. The higher the velocity of the incoming object, the smaller will be the fraction that the incoming momentum is of the total, and therefore the smaller will be the error incurred in such a simulation.

Since a laser pulse can readily be made to deposit energy densities corresponding to hypervelocity impacts, this appeared to be an economical experimental method for the approximate empirical study of the gross effects of such impacts in the principal lunar surface materials: namely, in lunar soil and in lunar rocks.

2. Experimental Method

The experimental method had to satisfy the following criteria:

The energy deposited had to be sufficiently concentrated so as to cause total evaporation of all constituents of the rock.

The pulse had to be of sufficiently short duration that the energy deposition is fast compared with the gas explosion caused.

The focused beam had to have a sharp outer edge so that there would not be a confusing zone of partial evaporation.

The total pulse energy and the impact area needed to be known.

All these points were sufficiently well assured in the experiments performed. The electron micrograph pictures show that the flow of liquefied rock around the craters was very similar to that in lunar specimens (Hartung *et al.*, 1972). The absence of any effects related to prolonged baking and outgassing of the samples shows that there are no important effects related to the liberation of small amounts of volatiles from the surrounds of the impact area.

The experimental set-up consisted of a ruby laser, a subsidiary helium-neon laser for lining up purposes, and a vacuum chamber with a sample holder precision stage. The procedure employed was that the ruby laser was aligned with the help of the gas laser and a film strip. The vacuum chamber was then evacuated to a pressure of

6×10^{-6} torr. Laser shots were then fired first on a film strip, then alternately on the rock surfaces and film strips. The pressure fluctuated during the experiments between 6×10^{-6} and 2×10^{-5} torr. Four small rock chips were selected for these experiments, originating from the following samples: 12063, 14310, 15535, and 15556. Among these samples the first two were rather fine grained, homogeneous rocks, 15535 a porphyritic basalt and 15556 a vesicular basalt rock. Three holes were made in each rock. The diameters of holes made in the film strips were measured under the microscope. The measurements are reported in Table I: (1) the diameter of the inner burned-out hole, (2) the diameter of the disks whitened by the beam. (See Figure 1.)

TABLE I

Laser shot No.	Target	Crater Diameter or burned out area (on film) diameter μm	'Splash' (on rocks) or bleached area (on film) diameter μm	Calculated crater depth μm
1	polaroid film	480	880	–
2	polaroid film	480	960	–
3	polaroid film	560	960	–
4	rock 15535	106	410	205
5	rock 15535	106	440	–
6	rock 15535 shown in Figure 2	180	410	206
7	polaroid film	400	800	–
8	polaroid film	400	960	–
9	polaroid film	480	960	–
10	rock 15556	94	410	227
11	rock 15556	87	440	–
12	rock 15556 shown in Figure 3	106	410	184
13	polaroid film	400	800	–
14	polaroid film	400	880	–
15	polaroid film	400	880	–
16	rock 12063	113	410	–
17	rock 12063	100	375	–
18	rock 12063 shown in Figure 4	125	410	250
19	polaroid film	400	800	–
20	polaroid film	320	800	–
21	polaroid film	320	800	–
22	rock 14310	112	340	–
23	rock 14310	106	410	–
24	rock 14310 shown in Figure 5	125	375	228
25	polaroid film	240	800	–
26	polaroid film	240	800	–
27	polaroid film	320	800	–
28	dust 14163 at 1 atm air	~1000	–	–
29	polaroid film	400	800	–
30	polaroid film	400	800	–
31	polaroid film	360	800	–
32	unbaked dust 14163 at 6×10^{-6} torr shown in Figure 6	~2500–3000	–	–
33	polaroid film	240	800	–
34	polaroid film	240	800	–
35	polaroid film	320	800	–
36	baked dust 14003 at 6×10^{-6} torr	~3000	–	–

The samples were examined with a scanning electron microscope. Stereo pictures were taken of at least one hole in each rock so the depth of these holes could be determined. (See Figures 2–5.) Single pictures were taken of all holes, a few at several magnifications.

The diameters of the holes reported in the table were measured on the SEM photo-

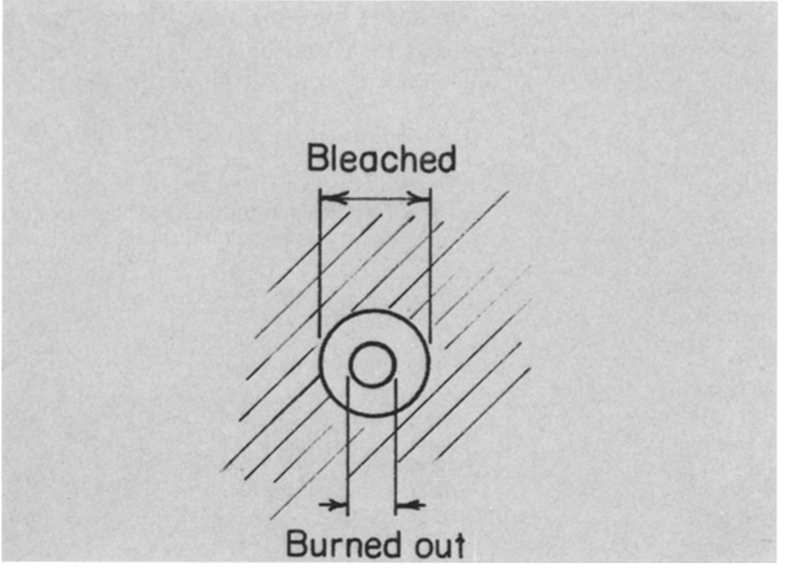

Fig. 1. Configuration of a laser hole made on a film strip.

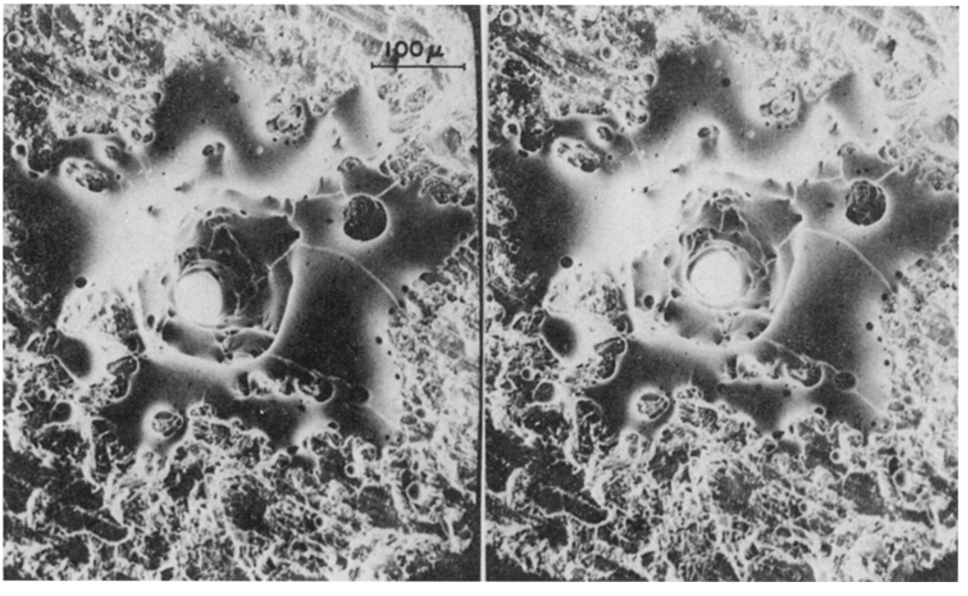

Fig. 2. Stereo pair of a scanning electron micrograph showing a laser hole in rock sample 15535.

graphs with the help of a series of calibrated concentric circles. The diameter is that of a circle having the closest area to the opening area of the hole. The depths of the holes were determined by the usual methods of photogrammetry with two pictures differing in aspect angle by 8°.

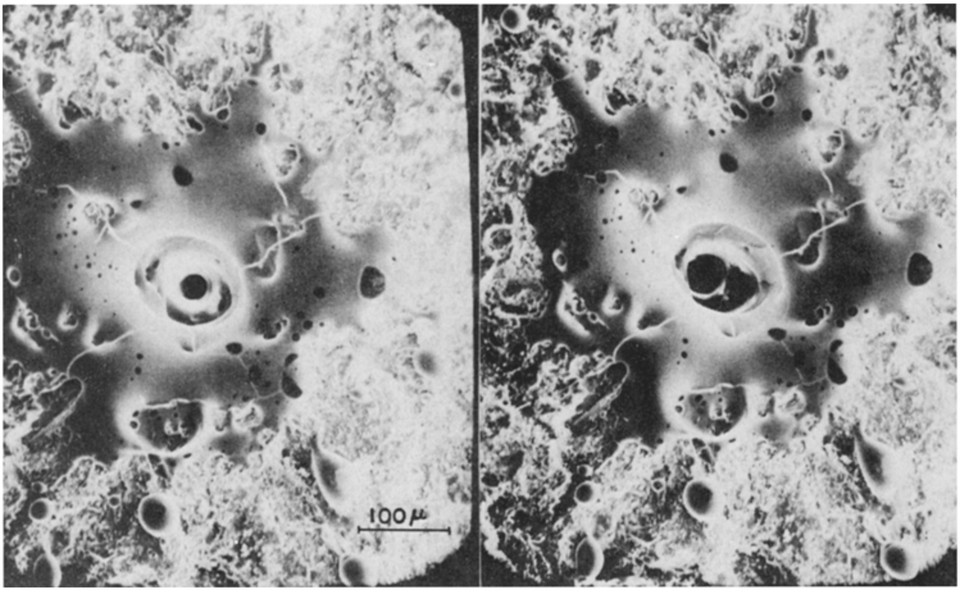

Fig. 3. Stereo pair of a scanning electron micrograph showing a laser hole in rock sample 15556.

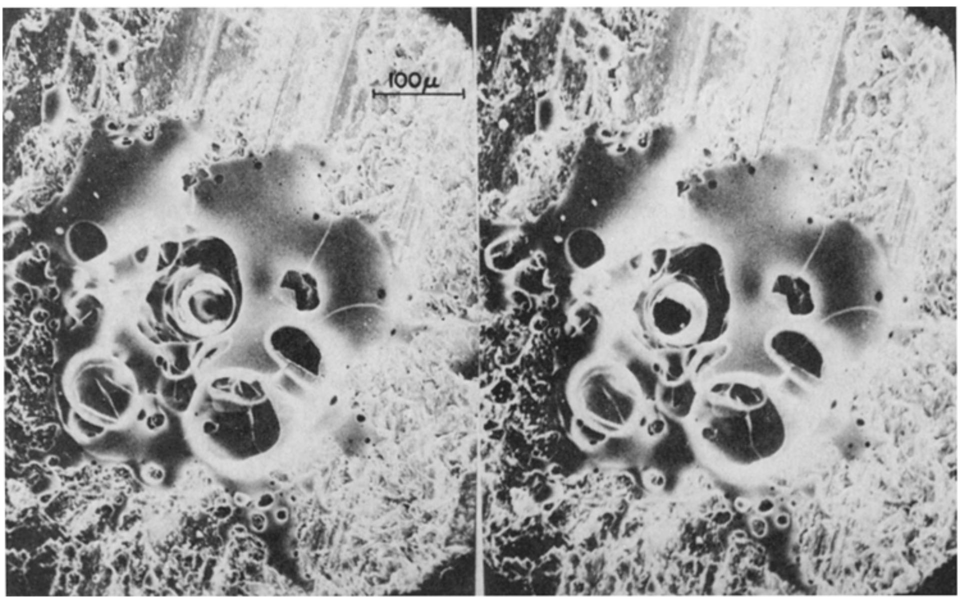

Fig. 4. Stereo pair of a scanning electron micrograph showing a laser hole in rock sample 12063.

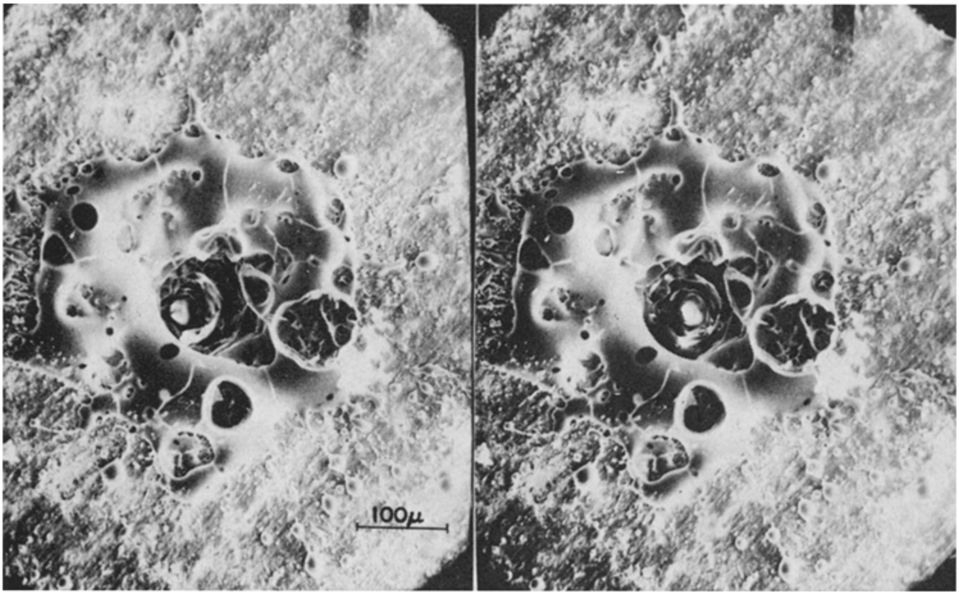

Fig. 5. Stereo pair of a scanning electron micrograph showing a laser hole in rock sample 14310.

Experiments with dust involved samples 14163 and 14003. We used these samples either directly from the dessicator or first baked out in a vacuum oven at 200°C for 24 h. The latter treatment did not seem to influence the result. The dust was compacted slightly in a small container and its surface smoothed out in order to be in a well defined plane on which the laser beam could be focused. The experimental procedure and the conditions were the same as for the rock samples. The dust samples were examined with an optical microscope and stereo pictures were taken of each laser hole (see Figure 6). The diameters of the holes reported in the table were measured with a calibrated grid.

The output energy of the laser was determined with a Hadron Energy Meter which has a ballistic thermopile device. This apparatus could not be placed under the beam collimator due to lack of space. Thus the energy of the uncollimated, unfocused beam was determined. The cross section of the latter was obtained by firing the laser onto a polaroid filmstrip. The cross section of the unfocused beam was very similar in size to the cross section of the entrance to the cavity of the energy meter and very little of the beam energy escaped the opening. The measured laser output at the input electric energy used in all our experiments was 4.86 ± 0.15 joules.

The duration of the laser pulse was not determined, the manufacturer measured it (though with a somewhat different power supply) to be 25 ns, which is shorter than required by a large margin.

The volumes of excavated material from the different rock and dust samples (V_{rock} and V_{dust}) were calculated using the data in the table and with the help of the stereo pictures. As a typical example, the diameter, of the hole in sample 14310 shown

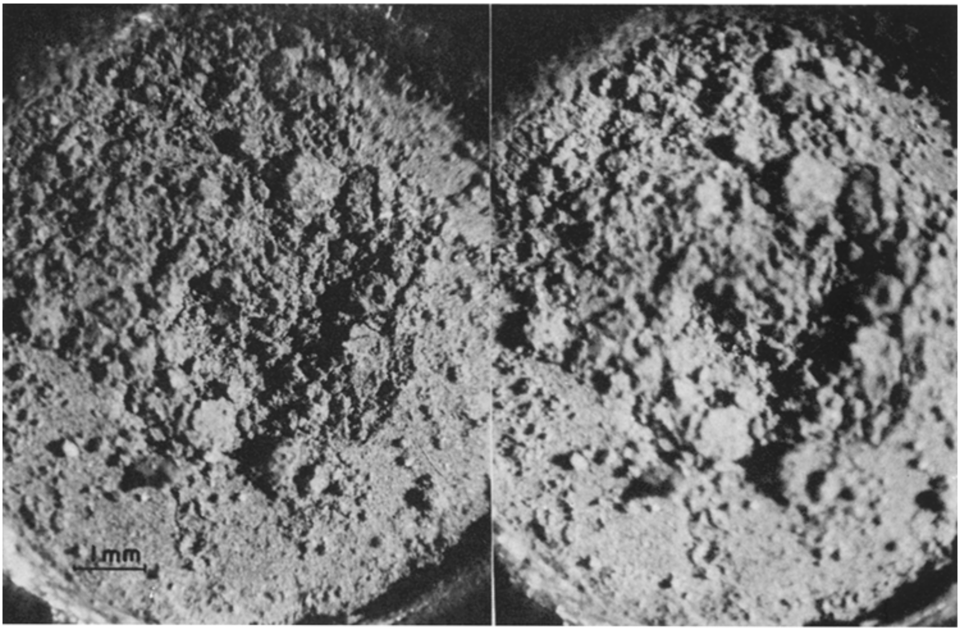

Fig. 6. Stereo pair of an optical micrograph showing a laser hole in dust sample 14163.

in Figure 5 is 125 μ, the depth is 228 μ. The shape of this hole is approximately cylindrical; thus its volume was calculated to be 2.79×10^{-3} mm^3. The surface area of the hole in sample 14163 shown in Figure 6 is 5.83 mm^2, the average depth is approximately 0.5 mm; thus its volume is 2.91 mm^3. V_{dust}/V_{rock} is, therefore, approximately equal to 10^3.

3. Experimental Results and Conclusions

The scanning electron microscope pictures obtained show a variety of interesting effects similar to those seen in similar sized craters on lunar rocks. This strongly suggests that indeed the processes were similar in essential aspects. In both cases one sees the clear effects of surface tension, an important force in small scale phenomena, in the smoothly rounded shapes and the occasional thin sheets of vitreous rock that appear to have frozen while gases were bubbling out.

The comparison of the volumes excavated for similar pulses impinging on solid rocks and on loose lunar soil could be carried out approximately. Although the holes in the soil had very indefinite shapes, and therefore the determination of excavated volume could not be exact, it is still clear that the material strength of the rock has a dominant effect on this scale, and that therefore the soil suffers very much more excavation. The best estimate resulting from this experimentation is that the volumes excavated in soil are approximately one thousand time those in rock. Thus a small clump of powder on the lunar surface would be destroyed in a time of the order of one thousandths of the time a similar sized rock would survive, if micrometeorites are the main agency for destruction. The discussion of this comparison cannot readily be applied to the speed of plowing over of smooth areas of soil, for there the material excavated at one impact shields and preserves another area. For this case one has to know the size distribution of the impacting objects. The data for the erosion rates of exposed small rocks, derived from cosmic ray effects, are almost certainly not dependent on any such shielding effects; they should be considered as erosion rates for rocks always kept 'clean' as we now find them.

Fleischer *et al.* (1971a, b) quote the mean erosion rate of rocks as between zero and 0.2 mm m.y.$^{-1}$, Crozaz *et al.* (1972) estimate the rate to be between 0.3 mm and 1.0 mm m.y.$^{-1}$ With a value of 0.1 mm m.y.$^{-1}$ the erosion rate for surfaces kept 'clean' is thus 0.01 cm m.y.$^{-1}$; if the volume removed in soil is 10^3 times as great then we have 10 cm m.y.$^{-1}$ as the erosion rate of a soil area which does not become shielded by the excavated material.

This last point is critical for the application of the result to lunar processes. A small clump of soil a few centimeters across, such as is commonly seen on the lunar ground, would be destroyed at this rate, and the rule could be applied to the approximate determination of the age of events that can be seen to have left a lumpy surface, such as the surrounds of small craters. Equally the result can be applied to the case that another transportation process exists that transports away any soil once it is liberated from slight adhesion by a micrometeorite impact; that is to say the case of an erosion process where the bottleneck is the rate of impacts. (This would be similar, for example, to the terrestrial erosion case where the rate of removal from bare rock is limited by the surface fracturing process, but where the subsequent removal of fractured rock is fast, leaving a surface of bare rock.) There are many indications that on lunar slopes a downhill transportation process exists, and that it is limited by some initial 'liberation' process of lunar soil, a process that is sensibly independent of the slope, and not by a slope dependent rate of movement (Gold, 1955, 1972). Thus, the present rate of denudation of mountains would be, on this basis, of the order of 10 cm m.y.$^{-1}$. If in earlier epochs the micrometeorite rates were higher, such as in the last phases of the accretion of the moon, this rate would also be correspondingly higher.

Gault, Hörz and Hartung, in the *Effects of Microcratering on the Lunar Surface* quote figures that are within a factor two of the above estimate for the amount of soil moved (presumably also for the assumption of no shielding effects). Our estimate is based on cosmic ray erosion data; Gault *et al.* (1972), on the other hand, depended in their calculation on micrometeoroid flux measurements. Agreement between the two estimates for the amount of soil moved by micrometeoroid bombardment of the lunar surface strengthens the correspondence between cosmic ray erosion and micrometeoroid flux estimates.

Acknowledgement

We thank Mr H. Eckelmann for his help with the photographic work. This research was supported by NASA Grant NGL-33-010-005.

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