total activity for sources *B* and *C* but less than one-sixth of the activity for source *A*; thus the average character number is depressed in the *A* region. It is encouraging that Baart, Lee, and Barrow (*4*) have recently reported results closely resembling those of Figs. 2 and 3, although their study was based on much less extensive data.

Comparison of Figs. 2 and 3 suggests that there may be a temporal

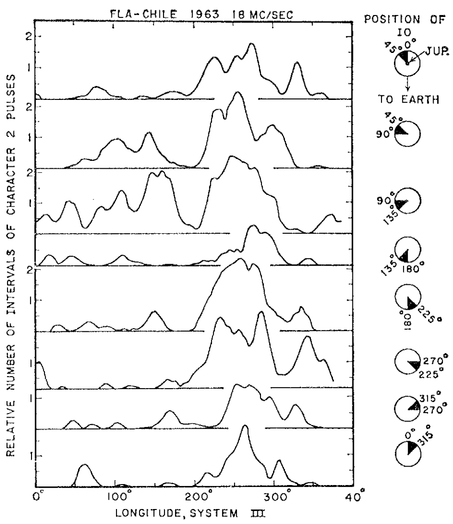


Fig. 4. Relative number of periods of 18-Mc/sec type-2 pulses as a function of System-III longitude for various positions of Io during 1963. Each profile represents the data received while Io was within the 45° shaded zone shown in the diagram at the right of that profile. Unity on the ordinate scale represents 25 30-second periods of radiation; three-point smoothing has been employed in the profiles in Figs. 4 and 5.

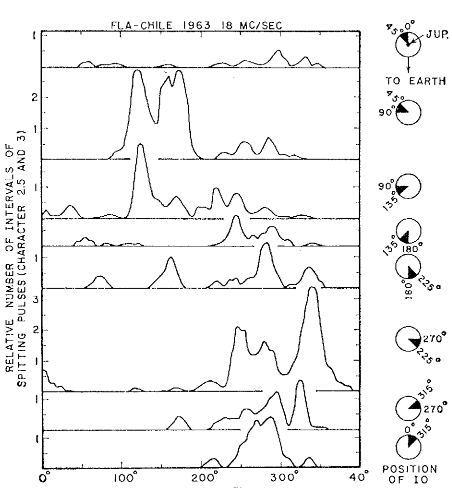


Fig. 5. Relative number of periods of 18-Mc/sec spitting pulses as a function of System-III longitude for various positions of Io during 1963. Unity on the ordinate scale represents ten 30-second periods of radiation.

variation in the relative amount of millisecond-pulse activity. In 1963 18 percent of all the 18-Mc/sec activity periods contained type-3 pulses, but in 1964 the figure dropped to 8.5 percent. The planet-wide average probability of emission for 18-Mc/sec pulses of all types declined from 0.173 in 1963 to 0.125 in 1964.

Since it is now well established that the position of the innermost Galilean satellite, Io, strongly influences the probability of Jovian decametric emission (*5*), an effort was made to see if this effect extends to pulse character. Figures 4 and 5 show profiles of 18-Mc/sec activity versus the System-III longitude of Jupiter's central meridian for normal and for spitting pulses, respectively; in each case the profile is drawn for eight different positions of Io relative to the Earth-Jupiter line. Figure 4 suggests that the type-2 activity of source *A* was relatively insensitive to the position of Io; while it shows the well-known enhancement when Io was roughly 90° or 240° from superior geocentric conjunction, a significant amount of activity was always present that was apparently unrelated to Io. On the other hand, Fig. 5 implies that the spitting activity from source *A* was somewhat more sensitive to the location of the satellite, peaking when Io was near western elongation; most striking of all is the sharp peaking of spitting activity in source *B* when Io was near 90°, and in source *C* when the satellite was near 240°.

The correlations demonstated in our studies can be used to support the hypothesis that the immediate environment of Jupiter itself must contribute in an important way to the burst structure. This point of view recently received additional encouragement from Riihimaa's report that the bursts from source *B* display a distinctive spectral fine structure (*6*). However, this conclusion should not be regarded as precluding interplanetary or ionospheric influences; for example, the mechanism responsible for generation and escape of the radiation may produce, among the several sources, disparate angular sizes or bandwidths. These factors, then, may well result in the radiation from each source interacting differently with the intervening medium.

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1 April 1966

## Luna 9 Pictures: Implications

Abstract. *Evidence from Luna 9 does not preclude the possibility that the moon may have a surface made up largely of very fine rock particles. The degree to which they attach to each other and the resulting firmness of the ground cannot yet be closely estimated.*

The successful experimentation with Luna 9 resulted in an interesting set of panoramic lunar surface pictures of high quality (see Fig. 1). The definition appears to be close to 1 mm for the nearest ground, and the illumination and range of gray scale is good enough to allow the detailed surface shapes to be seen. Owing to an unpredicted movement that took place some hours after the landing, views from different positions are available from which a stereoscopic picture can be constructed. Despite the clarity of this visual information, it seems to be impossible to make any definitive judgment concerning the mechanical properties of the soil or the processes responsible for the formations seen there.

Although the Soviet experimenters have asserted that the lunar surface is hard and dust-free, it is clear from their public statements (*1*) that they base this deduction on two observations: (i) the station did not sink appreciably into the surface, and (ii) the surface does not have the appearance which they expected of dust. In what follows we shall demonstrate that neither of these considerations excludes a dust-covered surface. The experimenters have also denied (*1*) having any instrumentation (such as soil-manipulating devices) on the station other than the television camera, a radiation detector, and housekeeping telemetry.

Many observers made the rapid judgment that the ground looked like solidified lava and all the many holes were bubbles and pores caused by foaming and degassing during solidification. There are, however, grave difficulties with this point of view, connected with a discussion of the rate of destruction by meteoritic infall, and of the optical, thermal, and radar properties of the surface. Also, the conclusion loses its force when it is realized that the appearance of a pulverized rock surface subjected to bombardment becomes almost indistinguishable from that of the Luna 9 pictures.

We have prepared such surfaces out of dry commercial cement powder (average particle size $\sim 1\ \mu$) mixed with powdered dyes to give a close approximation of the actual reflectivity of the lunar ground. All that is necessary is to throw powder at similar powder until the statistical nature of the surface is no longer changed by such further treatment (Fig. 2). The adhesion of any very fine rock powder is quite enough to maintain the steep or even vertical slopes on a small scale, and even substantial protuberances can be constructed by compaction of the powder. (We noted in experiments with small charges of high explosive that such compaction frequently occurs in the material ejected from a crater, leaving protuberances standing after the explosion that are nevertheless too friable to be picked up by hand.)

The smaller the grain size of a powder the more cohesive it tends to become. For this reason the appearance shown in the Luna 9 pictures would rule out a sand, as this would fail to maintain the steep slopes. It does not, however, rule out fine powders of particle size less than 10 or 20 $\mu$, of almost any mineral.

It has sometimes been thought that the discussion of a dust layer covering the lunar surface would imply a smooth, mobile, easily flowing material, with perhaps flow channels being visible on the surface, or a material of exceedingly low bearing capacity. Neither of these conclusions follows, as we have pointed out on many previous occasions (*2*). The discussion of rock dust concerns the process of formation of the present surface by the deposition of small particles, the destruction by impact, or the downhill movement of the fine debris. There has been no acceptable theory concerning the binding between the particles that may have developed, or the degree of compaction that they may have suffered. Without that knowledge the mechanical properties of a surface derived as a dust can cover a very wide range, and that possible range has not been diminished much even with the success of three Rangers and of Luna 9.

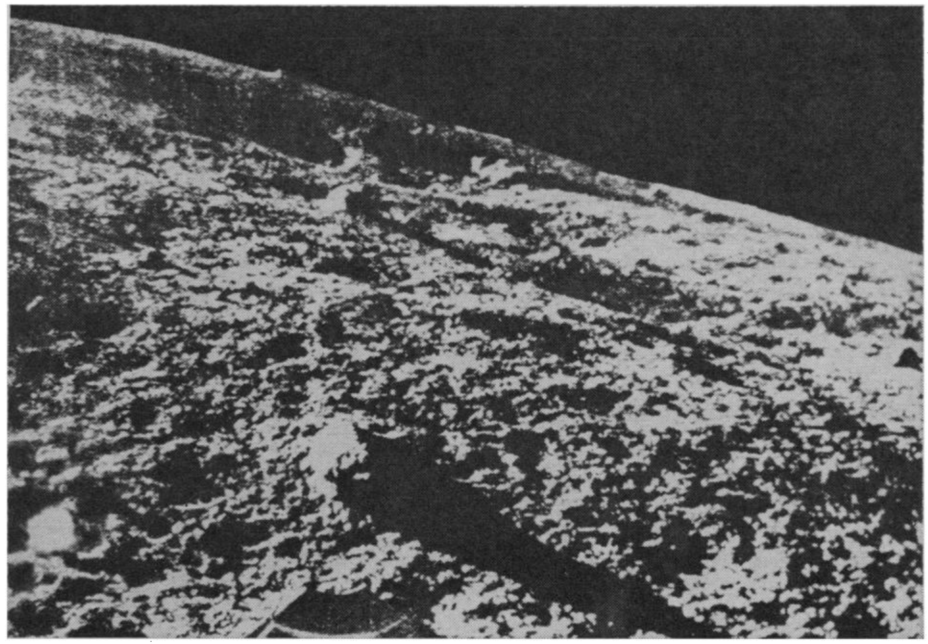

Fig. 1. A small portion of the surface of Oceanus Procellarum as photographed by Luna 9. The "rock" in the foreground is probably about 6 feet (2 m) away and is about 6 inches (15 cm) in diameter. As judged by stereoscopic viewing, the horizon appears to be the rim of a crater and is probably not more than 100 or 200 feet (30 or 60 m) away. [Courtesy *Tass*]

It had been clear for several years, through the radar data, that the moon's surface was completely rough on a scale of a few centimeters. This had been pointed out by several authors (*2, 3*) and the roughness now seen is thus in no way a surprise. It had been described that the ground must be only gently undulating when investigated on a scale of 10 cm or larger, but exceedingly rough when investigated on a smaller scale. The most likely type of roughness seemed that caused by impacts of a primary, secondary, or tertiary kind leading to densely overlapping little craters. That now seems a perfectly good description of what is in fact seen.

The vesicular lava hypothesis for the detailed appearance of the ground would require that external bombardment had not destroyed features even on a scale of centimeters. Yet estimates of the primary and secondary bombardment would imply no more than a few millions of years before these features would be completely obliterated. The solidification of the lava, on the other hand, cannot reasonably be thought of as having occurred less than several hundred million years ago. Meteoritic infall would have had to have been many orders of magnitude less than it is now, for the lava hypothesis to be correct.

This argument is not avoided by supposing, as some authors do, that meteoritic infall removes more material of the moon than it brings in. Even if each incoming particle were to liberate and throw back into space more than its own mass there is no doubt that a very much larger quantity of material would be shattered and moved. At any time a surface would be seen which had been worked over by meteoritic infall to some substantial depth—at any rate, to several centimeters. The fine structure of the ground that is seen can thus not be the original porosity of freezing lava even if the ground were basically made of lava.

The radar evidence concerning the difference in the radio properties of the young and old craters clearly requires the ground to have been plowed over by external agencies to such a depth as to be effective at 70-cm radio wavelength. That depth is thought to be several meters. The evidence is very clear-cut that each young crater is a much stronger radar scatterer than old craters of comparable diameter. Unless it were thought that the process of generation of craters had completely changed its nature between all the old craters and the small number of young ones, one would have to suppose that an external action had made the ground smoother and more radar absorbent in the course of time. The destruction and plowing over by meteorites would seem a perfectly satisfactory explanation for that. In that case, however, all but the youngest craters have been worked over to a depth of at least several meters. No original lava appearance could then be preserved.

Thermal data similarly require that the youngest craters differ from all the others in being made of more compact material. Exactly the same arguments apply, except that the total depth effectively tested by thermal measurements is much less.

The optical characteristics of the moon require a surface which is riddled with tunnels and holes pointing in all directions. The terrain of the nearest ground revealed in the Luna 9 panorama is not sufficiently complex to account for the lunar backscattering properties. An unresolved, more complex structure is clearly necessary, such as would be provided by fine cohesive powder.

Some limits on the mechanical properties of the lunar soil can be placed by the successful operation of Luna 9, and certain remarkable mechanical properties seem to be indicated. Firstly, the bearing strength was certainly enough to support the 2-foot (0.6-m) diameter sphere weighing 220 lb (100 kg), and thus approximately 40 lb (18 kg) on the moon. The depth of sinkage is not known, and unless other information is available the pictures would not reveal a sinkage of as much as 6 inches (15 cm). The lower limit to the static bearing load is then little over 0.1 lb/in.$^2$ (7 g/cm$^2$), which is a low figure even for uncompacted soils.

Initially some observers surmised that much more was implied, namely that the present resting place of Luna 9 was also the place at which it first impacted. This, however, seems quite unlikely. The mode of landing of Luna 9, one of ejecting the instrumented spherical package from a bus which executed the landing maneuver, was clearly a mode that allowed a much larger horizontal than vertical component of velocity for the final impact. Since it is harder to cancel with precision the horizontal components of velocity than the vertical, one assumes that this freedom will have been utilized and that the sphere in fact hit the surface initially at a glancing angle. For the velocities involved it would then skip, even on the lightest and fluffiest soils one might envisage (indeed it would also skip on water). It would then roll and finally come to rest, no doubt having an internal weight distribution that favors approximately the correct attitude. Its four petals that then opened will have helped to erect the package prior to its function. In this mode of landing the impact loading may have been large at first impact, but would not lead to digging in in any kind of soil. The final resting place after skipping and rolling would need to bear no more than the static weight. This is a method of landing an instrumented package which avoids many of the difficulties of other types of landing maneuvers, and which is particularly appropriate to a ground of unknown bearing capacity.

Fig. 2. A surface of dust in the laboratory. The picture shows an area about 2 feet by 3 feet (0.6 m by 0.9 m) and should be compared with the foreground of Fig. 1. The material is dry, commercial, Portland cement powder. The surface features were formed by throwing handfuls of cement powder at the surface to simulate the action of meteorite ejecta impacts on the lunar surface. The "rocks" are clumps of powder about 3 inches (8 cm) in diameter. The photograph was taken with low lighting and was defocused and printed with high contrast in order to simulate to a certain extent the conditions of Fig. 1. The same surface, but printed with less contrast, is shown on the cover of this issue of *Science*.

During the first day and between two picture-taking sequences, the package seems to have shifted so that the point of origin of the pictures was displaced by several inches. This is a very remarkable fact. There is even an indication of a second smaller movement also. From first reports it does not appear that the experimenters wish to attribute this to any internal activity or shifting of weights (*1*). If a passive object were thrown in a rocky desert anywhere on the earth it would be exceedingly unlikely that in the absence of wind or water it would move some hours after landing. It is very difficult to envision processes that have time constants of hours and that have a reasonable probability of occurring. Earthquakes are an exceedingly unlikely explanation, for if the moon had such violent earthquakes occurring as to make this event probable it would no doubt have shown many other visible effects in historically observed times. Thermal distortions of either the ground or the package are so small that one would have to suppose the package to have come to rest in an exceedingly delicately poised position, although it is possible that thermal expansion triggered a larger movement of the station, such as the motion of a petal. Yet, if these movements are the first information we have concerning mechanical properties of the lunar surface, we must clearly avoid forcing the explanation toward unlikely occurrences in order to preserve terrestrial-type surfaces. Rather, we must wonder whether the lunar surface is of a kind that makes this kind of event probable.

Plastic deformation time constants in any kind of rock material are many orders of magnitude longer. No significant deformation can be envisioned that would take a matter of hours to occur and then trigger a movement of larger amplitude. The only exception that we can now suggest would be time constants in the nature of those of an hourglass. If the lunar ground underneath Luna 9, and perhaps underneath most areas, had many hollow spaces, such as those that would be produced by all the many secondary impacts at moderate speeds, then it is conceivable that the additional loading may cause many such cavities to cave in. The time constants of caving in may then be given, just as in the case of an hourglass, by the many small particles that have to fall in sequence before a major structural change is made. If the addition of a new weight on the surface opens up a few new cracks in a very porous structure of not very firmly cemented small particles, then little collapses and landslides may appear until eventually the structural properties are so changed that a major collapse takes place.

The Luna 9 pictures clearly show a great many small holes. It is not clear whether some of these holes go deeply into the ground. A powder consisting of particles that have substantial cohesion would have the property that projectiles at rifle bullet speeds would easily make deep internal channels. The bombardment which is secondary to the larger meteoritic impacts will be of that nature, and the lunar ground may well be in the equilibrium configuration which is obtained by tunneling and collapse caused by primary and secondary impacts. That equilibrium may contain at any time a lot of features that are not far from collapse; under these circumstances, the movements of Luna 9 would be probable events.

This interpretation of the occurrence cannot of course be taken as more than a possibility. The lunar surface may be unusual in ways that we have not yet thought of. While we may refrain from accepting any one explanation of the phenomenon of the movements of Luna 9, we should not at this stage ignore an occurrence that constitutes one of the few pieces of information we have concerning the mechanical properties of the lunar surface.

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14 March 1966

## Drifting Organisms in the Precambrian Sea

Abstract. *Drag marks in the Upper Precambrian Winnall Beds of central Australia were made by semibuoyant flexible objects at least 15 centimeters long, which presumably were algae. This find extends the range of such marks into the Precambrian era and supplements the discovery of microflora in the same sedimentary sequence.*

While mapping the Henbury meteorite craters, Northern Territory, Australia, in 1963, I noted sedimentary features in Upper Precambrian rocks that indicate the presence of relatively large organisms. The recent discovery of preserved microorganisms in the same sedimentary sequence (*1*) adds interest to these observations.

The best examples of markings were found in fragments of a sandstone bed 15 cm thick that is intersected by crater 4 of the Henbury crater field (*2*), about 11 km WSW of the Henbury homestead. Although the outcrop of the bed is concealed, fragments ejected along ballistic trajectories during meteorite impact (*3*) form an ejecta ray 70 m long on the west side of the crater. The base of the sandstone bed preserves casts of grooves that had been scribed on the smooth upper surface of the bed below—presumably a shale bed.

Some of the grooves (as determined from their casts) are barely perceptible; others are as much as 3 mm across. The larger ones are rounded in cross section, and the smaller ones tend to be more angular. Some single grooves occur, but most of them are in parallel sets. Most sets are nearly straight throughout their length; a few show curves or even abrupt reversals of direction (Fig. 1). The width of the larger sets indicates that the dimension of the

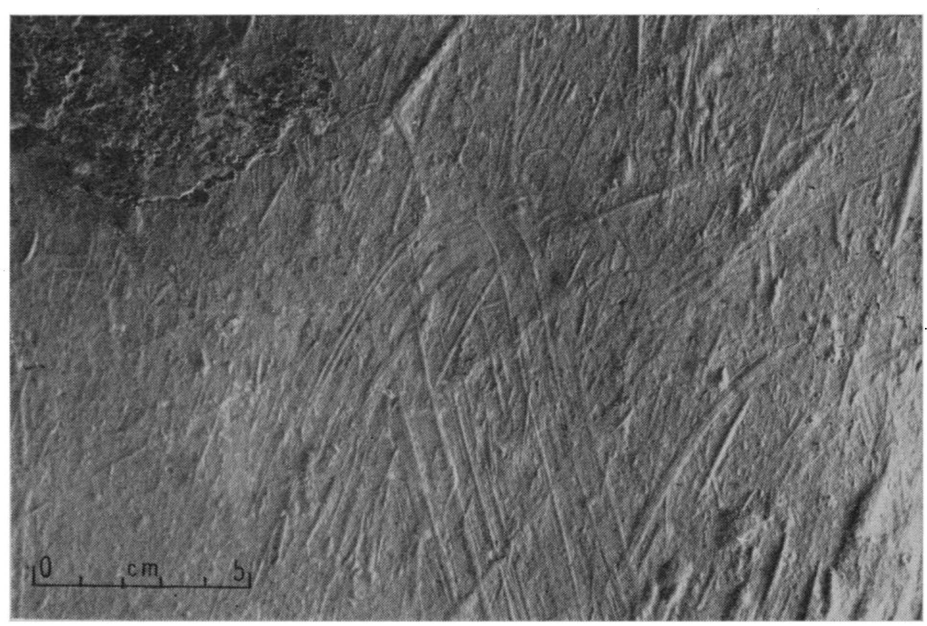


Fig. 1. Drag mark casts on sole of sandstone bed, showing an abrupt change in direction of more than 140°.