AN HYPOTHESIS CONCERNING THE EVOLUTION OF THE LUNAR SURFACE

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THE most widely held theory concerning the solar system is that the various bodies composing it were formed during the contraction of a large revolving disc-shaped cloud of dust and gas. Turbulence within this cloud is considered to have resulted in the formation of a number of regions of high concentration to which further matter was drawn by gravitational force. Such regions gradually developed into the sun and its satellites during which time virtually all the original materials became associated with one or other of these bodies. Urey[1] introduced the concept of "planetesimals", loose aggregates of dust held together initially by partially-frozen gases, which he suggested collided to form the protoplanets. These in turn acted as nuclei to which more material was attracted by gravitational force.

In accordance with this theory we might expect that the collisions of dust and planetesimals with a protoplanet must have been few initially but must have increased in frequency and energy as the protoplanet increased in size and gravitational influence. Depletion of the inter-planetary material, however, eventually would have decreased the infall, causing the collision rate to rise to a maximum and then drop in a roughly exponential fashion as in Fig. 1 A. Heat released by each collision would have increased the temperature of the entire planet. This would have been balanced to some degree by radiation, so that the temperature of the planet's surface (but not of its interior) probably followed a similar course to that of the collision frequency shown in Fig. 1 A. Eventually as the collision frequency and temperature dropped, however, a point must have been reached at which the surface solidified to form the lunar crust. It is the contention here that at this time (t_c, Fig. 1) the amount of inter-planetary material, while much less than its initial value, was still many times what it is today. Thus subsequent infall would have covered the bedrock with a layer of dust whose present average thickness is probably of the order of a kilometer. The various features visible on the moon's surface today might then simply be distortions of this layer caused by

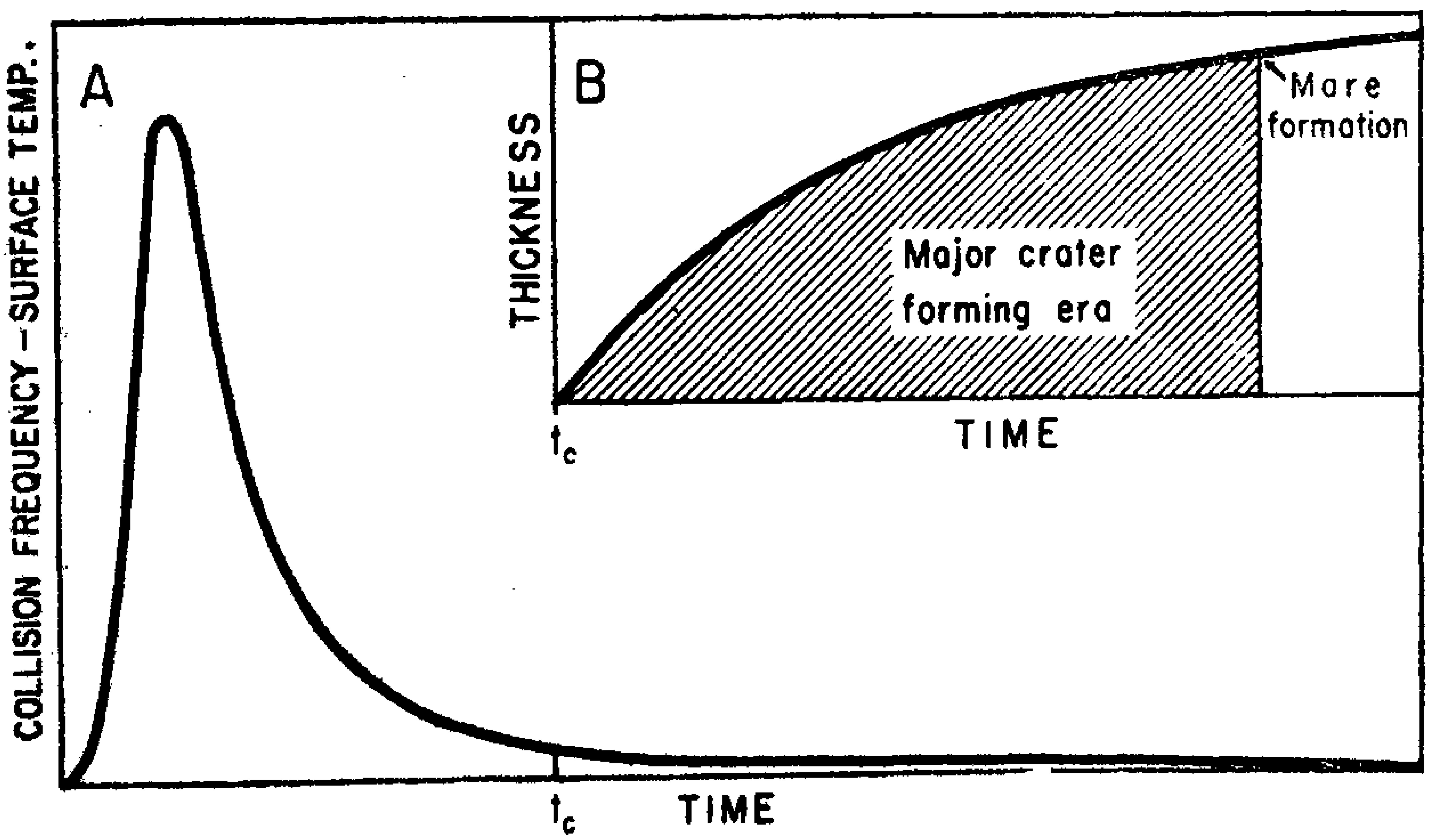

FIG. 1

collisions of planetesimals and other large bodies with it. This process may be illustrated by the following examples.

At the same time as the dust layer was building up, bombardment of the moon's surface by various sized planetesimals (and possibly meteorites at a later date) would also have been occurring at a rate which probably decreased with time in about the same fashion as the dust infall. These bodies arriving with high velocities would have resulted in the instantaneous vaporization of large amounts of material producing first of all a primary crater in the dust and underlying bedrock, and secondly an intense shock wave of gases, dust and rock fragments spreading out from the primary crater (Fig. 2 A), and peeling back the dust layer. The shock front would have continued to plow back the dust in the formation of a secondary crater until stopped by the accumulated mass of dust. In the meantime gas in the center of the crater would have escaped upward leaving a virtual vacuum near the point of impact. The gas present in the stalled shock wave, however, being compressed against the rim of the secondary crater, would next reverse direction, expanding back toward the crater center in the form of a reflected shock wave (Fig. 2 B). While most of the dust must have been carried away by the explosion, some would have failed to keep up with the shock front and falling back would have encountered the returning gases and be swept into the primary crater.

The returning shock wave would have had a relatively low energy but due to the circular shape of the crater, would have come to a focus near the crater center where the resulting turbulence could easily have given rise to one or more vortices. These would have tended to raise the dust into one or more peaks whose depressed summits would appear like central craters (Fig. 2 C) of the type frequently observed on the moon. Such peaks would not have been formed in all craters, however, and in particular would be missing from very small and very large craters. In the former, the central gas could not have escaped by the time the shock wave stalled, so no reflection could have occurred, while in the latter the reflected wave would have tended to disperse before reaching the center and at most only a low mound would have been formed. Thus the greatest frequency of central peak formation would be expected, on this hypothesis, to occur in medium size craters, a conclusion in agreement with observation.[2]

Some of the more recently formed craters (notably Tycho and Copernicus) are lighter in colour and are surrounded by lighter material. To explain such differences in albedo we need only assume that the cosmic dust is comparatively dark and the bedrock light. This is quite likely since Southworth[3] has estimated the albedo of interplanetary dust as 0·03. Thus fragments thrown from the primary crater will tend to lighten the surface on which they fall forming a light-coloured pattern surrounding the point of impact. The ray system of Tycho is one such pattern, likely resulting from a very high velocity collision which hurled fragments of bedrock great distances. The splash pattern surrounding Copernicus on the other hand could be evidence of a much lower impact velocity which produced shorter trajectories of bedrock debris. The rock fragments forming both types of patterns will have struck the dust surfaces at low velocities and will therefore have made only small craters. Such objects lying in the bottom of these depressions, will be in shadow during the early and late phases of the moon but will be directly illuminated, and their light colour most evident, during full-moon, at which time the rays are seen to have their greatest brightness.

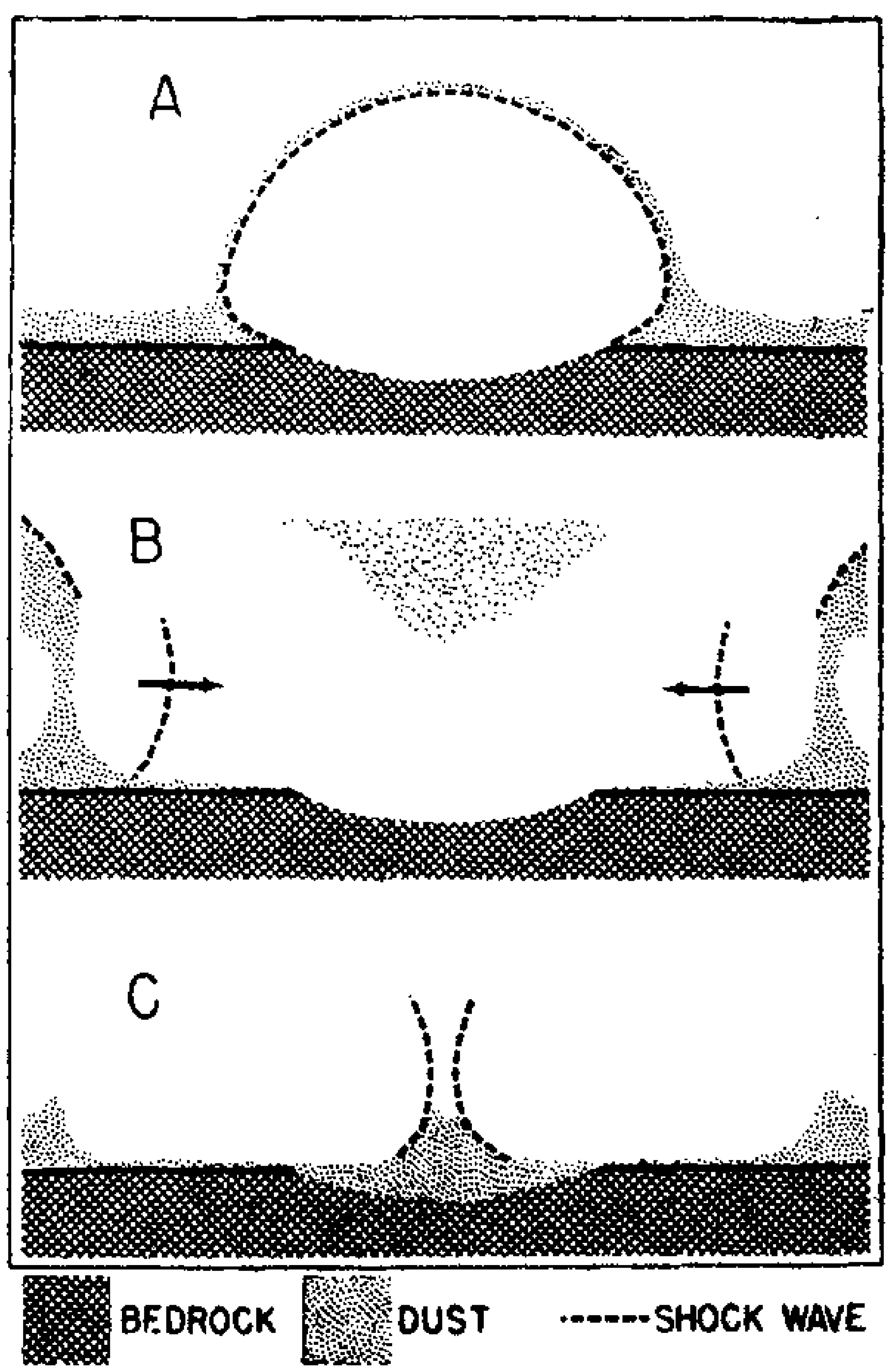

FIG. 2

Although most craters would have been formed during a relatively short period in the history of the moon (Fig. 1 B) there would be a considerable difference in the appearance of those formed at the beginning of the dust deposition and those formed later. The older craters would be the shallowest by virtue of their being formed in a relatively shallow layer and as a result of the subsequent fall of dust which would tend to erode and cover them, softening their outline. Those formed later however would have been deeper initially and less subject to this form of obliteration. Rock debris thrown up by earlier collisions would be churned up repeatedly by following explosions, producing a middle gray mixture of rock fragments and cosmic dust characteristic of the much-pitted southern uplands.

This theory of crater formation has two advantages over other collision theories. Firstly, it predicts the formation of wide shallow structures, similar to lunar craters. Secondly, for a given collisional energy, a much larger crater will be formed in loose dust than in solid rock, thus explaining the fact that earth meteoritic craters appear to be smaller than those on the moon.

The maria, on the other hand, are dark, and must on the above assumptions be considered to be covered mainly by cosmic dust with little contamination by rock debris. Except where their expanse is broken by a few craters, these structures appear to be fairly smooth and to have a lower altitude than the rest of the moon's surface. There are two other observations however which are of prime importance in explaining their origin. The first concerns the craters whose number per unit area of marial plains is much less than that elsewhere on the moon's surface and is furthermore constant for all the maria.[4] This indicates that the maria are of more recent vintage than the majority of craters and what is most important, are all of about the same age. Secondly, the maria themselves are not distributed evenly over the whole surface of the moon. The greatest expanse of marial plains is found in the eastern hemisphere of the visible side of the moon, whereas the obverse side as photographed by Luniks III and IV is almost devoid of these structures.[5] These facts indicate that the maria are not distributed evenly in either time or space and so may be the product of a single cataclysmic event occurring at a time when the majority of craters had already been formed (Fig. 1B).

It is suggested that such an event may have been the collision between the moon and a number of volatile bodies such as planetesimals from the region of the major planets, or cometary fragments. These bodies probably consisted of frozen gases (most likely ammonia, water and methane) interspersed with cosmic dust (Whipple[6]). It is likely that they were much more common during the early history of the solar system than at present, so there is a reasonable probability that the earth-moon system intersected the orbit of a large cluster or group of these objects. Since they possessed so much volatile material these fragments, on striking the moon, would have stirred up enormous areas of the dust layer. Where large discrete masses of these materials struck, well-defined crater-like maria such as Imbrium, Serenitatas and Crisium would have been formed. Less well-defined maria such as Nubium and Oceanus Procellarum probably resulted from a veritable hail storm of smaller ice fragments evaporating on collision to produce a seething mass of gases which would have levelled existing craters to varying extents and suspended most of the dust layer temporarily. The finer cosmic dust would have been more readily suspended than the bedrock fragments and would have been the last to settle once the gases had dispersed.

It is also possible that such objects contained a large amount of slushy ice which would have melted, but not completely vaporized, on collision. This would have left behind large expanses of a water-dust slurry from which first the rock fragments and then the cosmic dust would have settled. For a short time after this, then, the moon would have had an atmosphere and true "seas" of a water-ammonia solution. Eventually, however, loss of the atmosphere would have occurred, followed by evaporation of the seas.

In either case there would have resulted large areas virtually devoid of craters and darkened in colour by a top layer of cosmic dust. Maria Nubium, Humerum, Imbrium and Oceanus Procellarum all appear to have been formed at the same time, as there is not a complete dividing wall between them. Other nearby maria may also have been formed contemporaneously with these areas by the main body of fragments approaching from the north-east. Most of those fragments not striking either the earth or the moon would have continued on in space. A few, however, would have taken up various orbits about the earth, and some of these probably struck the moon from different angles before finally evaporating. Thus a few smaller maria would have been formed in regions remote from the main collision area. The moon appears to have been sufficiently plastic at this stage to have yielded under the tremendous onslaught of the mare-forming bodies producing depressions in, and cracking of, the moon's crust. Subsidence of the dust into these cracks could have produced the rilles found mostly in and around the maria.

Gold[7] has also suggested that the maria consist of a thick layer of dust. He considers, however, that the dust originated from erosion of rocks in the uplands and that it then became fluidized, flowing down into the depressed areas like water, to form the maria. This theory has been seriously challenged as a result of the recent Luna 9 photographs which provided a close-up of the moon's surface.[8] From these it is quite obvious that no loose dust is present in the area surveyed by the cameras.[9] According to the above theory this would simply indicate that during the eons since deposition of the dust layer and formation of the maria, constant bombardment by micrometeorites and solar particles has resulted in a sintering of the dust surface into a hard rough crust. This crust, which may be centimeters or even meters thick probably covers the entire surface of the moon except those areas recently subjected to bombardments of sufficient energy to shatter the crust and displace the underlying dust.

It has been pointed out by several workers that the earth is likely to have been in collision with a number of comets during its history. This would apply to all the terrestrial planets, all of which must have received at least some of their atmospheric gases and free water by this means. The amount of free water on the earth, however, appears to be so much greater than on either Venus or Mars that some special circumstance must have arisen to provide water to the earth alone. The collision of the earth with a swarm of comets or volatile planetesimals such as proposed above could have formed ocean basins, added the necessary water and furthermore would have provided large quantities of carbon compounds, which as Oro has suggested, contributed to the initial phases of life. In fact, such an event may well have been an essential prerequisite to the origin of life on the earth.

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CARNEGIE INSTITUTION OF WASHINGTON—YEAR BOOK 64 *

THE *Year Book* 64 of the Carnegie Institution of Washington contains reports on current research from all departments of the Institution for the year July 1, 1964 to June 30, 1965.

Spectroscopic observations of quasi stellar sources have become of special importance to cosmology, and the 200-inch Hale telescope combined with the Schmidt camera has been providing unique opportunities in this field to workers of the Mount Wilson and Palomar Observatories. During the year spectacular red-shifts for five quasi stellar sources have been measured. The most distant of the five, 3 C 9, showed the Lyman alpha line shifted from its normal position of 1216 Å to 3660 Å, giving a red-shift $\Delta\lambda/\lambda_0 = 2{\cdot}012$.

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