LETTERS TO THE EDITORS

PHYSICAL SCIENCES

Origin of the Lunar Craters and Maria

I AM prompted to tender a few pertinent comments on the recent communication by Prof. Zdeněk Kopal[1].

The physiographical similarity between many of the lunar craters and those produced by man-made explosions has been pointed out by Baldwin[2], and, if one dare assume that at least some of the lunar craters were produced by impacting objects, one can make use of this similarity and the present state of knowledge on the strong shock hydrodynamics of explosive cratering in estimating the relative energies involved and—with a slightly greater uncertainty—the masses which produced them. My own analysis, which I hope to publish shortly, leads me to believe that Baldwin's energy figures should be revised sharply upwards, that is, that the kinetic energy of an impacting mass would have to be of the order of 10^{28} ergs to produce a crater twenty miles in diameter, and one expects the diameter to vary as the cube-root of the impacting energy. While the energy partition in a venting underground explosion depends critically on the depth of penetration, present experience indicates that as much as one-half the incident energy may be absorbed in ground shock for deeply penetrating explosions. Most of this energy is absorbed in irreversible heating of the rock in a very short distance, and when the shock pressures have degraded to the order of the elastic strength of rocks (about 1 kilobar), the energy available for propagation as seismic waves is not likely to be more than 1 per cent of the incident energy.

Thus we are back again to a figure like 10^{26} ergs of seismic energy emanating from an impact capable of producing a crater 20 miles in diameter. I believe also that it is not unfair to seismologists to state that there is a disagreement of at least three orders of magnitude in the total seismic energy from the largest terrestrial earthquakes, with 10^{25} ergs as the lowest estimate. Thus it is not unreasonable to presume that the formation of a crater as large as Alphonsus would be accompanied by a moonquake of comparable intensity to the largest earthquakes, and the presence of craters twice as large as Alphonsus implies an increase of one order of magnitude in the seismic energy. In contradistinction to earthquakes, the seismic energy from an explosion is preferentially concentrated in the P-phase, with very little going into S-phase (Rayleigh waves), and the region undergoing substantial Earth motion is confined to within one or two crater radii. It appears extremely doubtful that even the largest craters, if attributable to impact, would exhibit widespread damage visible from the Earth.

With regard to conditions at the anti-focus, even if one disregards the difference in arrival times (of Rayleigh waves exclusively) due to anisotropy and non-sphericity of the lunar globe, and admits an energy concentration an order of magnitude below that at the source, there is little reason to expect any pronounced physical disturbance at the assumed caustic. The early processes in the production of seismic energy at the source are irreversible; certainly no crater would be formed. A more likely situation would be the local enhancement of ground motion, but probably never exceeding the elastic limit of the rock.

Prof. Kopal postulates that an impacting cometary mass possessing 10^{31} ergs of kinetic energy could produce 10^{20} gm. of molten lava. The results of the 'Ranier' underground atomic test in Nevada[3] indicate that less than 0·1 per cent of the total mass of material within the fracture zone was fused, and that cooling of the entire volume to temperatures like 100° C. took place in less than 1 hr. Although the equivalent of one-half the thermal energy of the bomb was required to fuse this mass of material, resolidification (if it was ever melted at all) occurred almost immediately, and the fused material was brecciated and intermingled with other debris when the cavity collapsed. In the case of a surface, or near surface, explosion, one would expect that the fused material would be thrown out of the crater along with the other debris, and not collected as a molten pool in the bottom of the crater. The distribution of fused material around the Canyon Diablo crater already supports this hypothesis.

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California. Jan. 29.

[1] Kopal, Z., *Nature*, **183**, 169 (1959).
[2] Baldwin, R. B., "The Face of the Moon" (Chicago Univ. Press, 1949).
[3] Preliminary Report of Operation Plumbob, University of California Radiation Laboratory, Report 5124).

IF Dr. van Dorn is right in concluding that the energies of meteor impacts necessary to produce lunar craters of given size are actually about 100 times larger than those postulated by Baldwin, the seismic arguments put forward in my letter of January 17 would be correspondingly strengthened; for the available estimates of the largest energies of terrestrial earthquakes range between 10^{23} and 10^{27} ergs, with 10^{25} ergs as a fair average (Gutenberg, 1958).

The fact that seismic energies of terrestrial surface explosions are spent preferentially in the P-waves is of no direct lunar relevance; for, first, the epicentres of lunar meteor explosions should be at least a few thousand yards deep (that is, far from pure surface phenomena in the terrestrial sense); and, secondly, the much lower gravity would allow S-waves on the Moon to attain greater amplitudes than on the Earth. Moreover, the real point of my communication was to direct attention, not to the damage caused by seismic waves in the immediate neighbourhood of an impact, but rather to the cumulative effects which hundreds of thousands of such occurrences would be bound to entail, and which have not been paid any attention in all previous work.

The focusing (however imperfect) of lunar S-waves in the anti-focal region should produce increased