ON THE ORIGIN OF LARGE LUNAR CRATERS AND ROUND MARIA

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Abstract

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ON THE ORIGIN OF LARGE LUNAR CRATERS AND ROUND MARIA

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In substantiating the meteoritic hypothesis of the formation of the lunar relief, extrapolated empirical relationships are used that were established for industrial and military explosions, as well as for terrestrial meteoritic craters. Recent work on modeling large ejection explosions ([6],[7]) has shown that such extrapolations contain substantial errors.

The characteristic size of a crater is its radius, determined by the energy of the explosion, the depth of the explosion center, the physico-mechanical properties of the medium, and the acceleration of gravity. As applied to the Moon, the radii of craters and the acceleration of gravity are known, and the density and strength of the rocks are known with a certain reliability. The depth of the explosion center (the limiting depth of meteorite penetration) can be estimated with sufficient rigor.

The established relationships connecting dimensionless parameters with the energy of an explosion ([6]), as applied to lunar conditions, are valid in the ranges: energies 10^{26}—10^{32} ergs, crater radii 0.8—200 km ($n = 0.6$—3.5), which corresponds to the observed characteristic dimensions of lunar craters and round maria, as well as to the accepted values of the energies of meteoritic explosions ([1],[2] ,[8]).

In accordance with the available estimates of meteorite velocities (up to 80 km/sec) and their densities (stony, 3 g/cm^3; iron-nickel, 8 g/cm^3), the penetration depth of meteorites (of spherical shape) can be calculated:

$$W = \frac{2M}{C_x S \rho} \ln \frac{U_0}{U} = \frac{4}{3} \frac{\sigma}{\rho} r \ln \frac{U_0}{U}, \tag{1}$$

where M is the mass of the meteorite, $C_x = 2$ is the dimensionless drag coefficient, S is the area of the midsection of the meteorite, σ is the density of the meteorite, ρ is the density of the medium, r is the radius of the meteorite, U is the velocity of the meteorite at which penetration practically ceases (in the calculations taken as 4 km/sec), and U_0 is the initial velocity of the meteorite.

Fig. 1 and Fig. 2

Figure 1: Fig. 1 and Fig. 2

Taking the energy and velocity of the meteorite as parameters and expressing the radius of the meteorite through E, U_0, and σ, formula (1) can be rewritten as:

$$W = \frac{4}{3}\frac{\sigma}{\rho}\left(\frac{E}{\frac{4}{3}\pi\sigma U_0^2}\right)^{1/3} \ln\frac{U_0}{U}. \tag{2}$$

The results of calculating the penetration depth are given in Table 2 and in Fig. 1. As is seen from Fig. 1, at $E = \text{const}$, W depends extremally on the velocity. The maximum penetration depth is realized at $V = 20$ km/sec.

The dependence of the radius of the explosion crater on the depth of the explosion center also has an extremal character. Using the experimental relationships (^{6}), the optimum depths and the corresponding maximum crater radii that could arise under lunar conditions were found.

in explosions with energies of 10^{26}–10^{32} ergs (Fig. 2, Table 1). In calculating the radii of lunar craters arising from explosions, the following was assumed: $g = 162$ cm/sec^2; $\rho = 3$ g/cm^3; δ (strength) $= 300$ kgf/cm^2. Using the dependences presented (Fig. 2), the radii of lunar craters that could have arisen as a result of meteoritic explosions were determined (Table 2). In doing so it was assumed that $V = 20$ km/sec, as ensuring the maximum penetration depth.

As is seen from Table 1, the maximum diameters of funnels arising under lunar conditions in explosions with $E = 10^{26}$–10^{32} ergs correspond to the observed diameters of lunar craters, but are smaller than the diameters of the round seas. However, the depths at which the centers of the explosions must be located in order to produce funnels with such (maximum) diameters differ substantially from the limiting penetration depths of meteorites (see Fig. 1, Table 2).

Fig. 1. Dependence of penetration depth on velocity for iron-nickel (A) and stony (B) meteorites (E in ergs)

Fig. 2. Dependence of the radius of a lunar explosion funnel on the depth of the explosion center and the explosion energy

The question of the relationship between the limiting penetration depths of meteorites and the optimal depths of location of explosion centers is best considered in concrete examples.

Table 1

Explosion energy E, ergs	10^{26}	10^{27}	10^{28}	10^{29}	10^{30}	10^{31}	10^{32}
Optimal depth of the explosion center W, km	3	6	10	20	35	60	110
Funnel radius R, km	4.5	9	17	32	58	106	190

According to the proponents of the meteoritic hypothesis, the energy of meteoritic explosions that caused the formation of large craters ($D \geq 150$ km) and seas was 10^{30}–10^{32} ergs (2). In particular, for the crater Clavius ($D = 230$ km) $E = 2.1 \cdot 10^{31}$ ergs (8). From the graphs (Figs. 1, 2) of the dependences $W = F_1(E, V, \sigma)$ and $R = F_2(E_2, W)$, we find that the maximum penetration depth of the meteorite will be 33 km, and, correspondingly, the radius of the explosion funnel 90 km, which is much smaller than the dimensions of the crater Clavius. The number of such

examples can be continued (the craters Grimaldi, Schickard, Riccioli, Schiller, etc.). At the same time, it should be noted that for craters with $D < 100$ km (Tycho, Aristillus, Kepler, Bessel) there is agreement between the observed diameters and the maximum diameters that could have arisen in meteoritic explosions (at $V = 20$ km/sec; $\sigma = 8$ g/cm^3; $E = 1.07 \cdot 10^{30};\ 2.88 \cdot 10^{29};\ 5.37 \cdot 10^{28};\ 6.31 \cdot 10^{27}$ ergs, respectively (^{8})).

An even more clearly marked discrepancy appears when the lunar maria are considered. The diameters of most lunar maria are 450-600 km, and in individual cases they reach 700-1000 km. From the graph (Fig. 2) it follows that at $E = 10^{32}$ ergs the limiting radius of the explosion funnel realizable under lunar conditions will be 190 km. In this case the center of the explosion must be located at a depth of 110 km. The limiting calculated penetration depth of a meteorite with $E = 10^{32}$ ergs is 65 km; accordingly, the radius of the explosion funnel will be 170 km, which is also much smaller than the dimensions of the lunar maria.

Table 2

Energy E (ergs)	Penetration depth of the meteorite into W at $V = 20$ km/sec (km), stony	Penetration depth of the meteorite into W at $V = 20$ km/sec (km), iron	Funnel radius R (km), stony	Funnel radius R (km), iron	Energy E (ergs)	Penetration depth of the meteorite into W at $V = 20$ km/sec (km), stony	Penetration depth of the meteorite into W at $V = 20$ km/sec (km), iron	Funnel radius R (km), stony	Funnel radius R (km), iron
10^{26}	0.34	0.66	1.4	2.35					
10^{27}	0.73	1.41	3.5	5.3	10^{30}	7.32	14.1	31.0	43.0
10^{28}	1.57	3.04	7.0	10.0	10^{31}	15.7	30.4	64.0	89.0
10^{29}	3.4	6.6	13.0	20.0	10^{32}	34.0	65.6	128.0	170.0

Thus, as a result of meteoritic explosions with energies 10^{30}–10^{31} ergs, craters with a diameter greater than 180 km could not have formed. Similarly, lunar maria could not have formed in explosions with $E = 10^{32}$ ergs.

The error in the approach of supporters of the explosive meteoritic origin of large craters and maria ($^{1-5}$) consists in the fact that the depth factor was not taken into account by them, and the characteristic size of the funnel—the radius—was found as a function of energy, under the assumption that the explosion occurs at the optimal depth. As was shown above, this assumption is erroneous.

Neglecting the depth of the location of the explosion center also leads to other inaccuracies. The conclusion that, for equal masses and velocities (i.e., equal energies), explosions of iron and stony meteorites will lead to the formation of identical craters (^{8}) is incorrect. From Table 2 it is seen that the penetration depth of an iron meteorite is approximately twice that of a stony one; it is easy to verify that, to form funnels of identical dimensions, the energy of the stony meteorite must be approximately an order of magnitude greater than the energy of the iron meteorite (Table 2).

It is necessary to note that in all the calculations presented, initial conditions were adopted that ensure maximum agreement with the results following from the meteoritic hypothesis. In addition, in determining the maximum penetration depth of the meteorite, following the supporters of the meteoritic hypothesis, it was assumed that the explosion begins after penetration is completed. In reality, however, the meteoritic explosion begins from the moment of impact, as a result of which the actual (effective) depth of the explosion center will be appreciably less than the calculated penetration depth given in Table 2. Accordingly, the values found for the funnel radii are certainly overestimated. Knowing the velocity of propagation of the detonation wave in the meteorite, one can estimate fairly accurately at what depth (after what time following impact) all the material will explode.

meteorite. However, consideration of this question is not part of the task of the present work.

Thus, despite optimization of the initial conditions, it has not been possible to achieve satisfactory agreement between the results of experimental studies and the conclusions following from the meteorite hypothesis. From the standpoint of the meteorite hypothesis, within the framework of the theory of a concentrated explosion with ejection, the formation of large craters and maria cannot be explained.

The question of the causes of the origin of large lunar craters and maria may be resolved along two alternative lines:

1. To consider their formation using the theory of the explosion of laid charges. In the physics of the phenomenon this is closer to the explosion of a large meteorite than to an explosion with ejection. In this case, however, it is unlikely that the energy difficulties can be overcome, since the crater-forming effect of laid explosions is smaller than that of explosions with ejection.
2. The formation of large craters and maria is due to endogenous causes.

The latter appears more probable.

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Note: Figure translations are in progress. See original paper for figures.