ON THE ORIGIN OF THE LARGE LUNAR CRATERS AND CIRCULAR MARIA

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ERRATA

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(G.S. Shteinberg: On the origin of the large lunar craters and circular maria)

Page 1, line 5 of second paragraph, for <u>precision</u> read <u>confidence</u>.
Page 2, line 7: read δ (strength) = 300 kg/cm^2.
Page 3, line 4: read $2.1 \cdot 10^{31}$ ergs [8].

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G.S. Shteinberg

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The meteoritic hypothesis of the formation of the lunar relief is based on extrapolation of empirical relationships established for industrial and military explosion craters, and also on terrestrial meteorite craters. Recent work on the modeling of major ejective explosions [6, 7] has shown that such extrapolations entail serious errors.

A characteristic dimension of a crater is the radius, which is determined by the energy of the explosion, by the depth to the explosion center, by the physico-mechanical properties of the medium, and by the acceleration of gravity. As regards the Moon, the crater radii and the acceleration of gravity are known; also, to some degree of precision, the density and strength of the rocks. The depth of the explosion-center (the limiting depth of the meteorite penetration) can be rigorously enough calculated.

Applied to lunar conditions, the relationships established between the dimensionless parameters and the explosion energy [6] are correct and proper within the energy range $10^{26} - 10^{32}$ ergs and crater radius range 0.8 — 200 km ($n = 0.6$—3.5), agreeing with the observed characteristic sizes of the lunar craters and circular maria and also with accepted values of the energy of meteorite explosions [1, 2, 8].

According to existing estimates of meteorite velocity (up to 80 km/sec) and density (stony meteorites 3 g/cm^3, iron-nickel meteorites 8 g/cm^3), the penetration depth of meteorites (of spherical shape) may be calculated as:

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

where M = mass of the meteorite, $C_x = 2$ = dimensionless streamlining coefficient, S = transverse cross-sectional area of the meteorite, σ = density of the meteorite, ρ = density of the medium, r = radius of the meteorite, U = meteorite velocity at which penetration practically ends (in calculations this is taken as 4 km/sec), U_0 = initial velocity of the meteorite.

Taking the meteorite energy and velocity as parameters and expressing the meteorite radius in terms of E, U_0 and σ, we may rewrite formula (1) as:

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

The calculated results for the depth of penetration are shown in Table 2 and Fig. 1. As we see from Fig. 1, for E = constant the depth W has a peaked dependence on the velocity. The maximum depth of penetration is attained at V = 20 km/sec.

The relationship between the explosion pit radius and the depth of the explosion center also exhibits a maximum. We used experimentally established relationships [6] to find the optimum depths and the corresponding maximum radii of the pits that could be formed under lunar conditions by explosions with energies $10^{26} - 10^{32}$ ergs (Fig. 2, Table 1). In calculating the radii of explosion-formed lunar craters we employed values g = 162 cm/sec^2, ρ = $3g/cm^3$, and δ = (strength) - 300 kg/cm^2. With the relationships here given (Fig. 2) we determined the radii of lunar craters that could be formed by meteorite explosions (Table 2), taking V = 20 km/sec as the velocity ensuring the maximum depth of penetration.

TABLE 1

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

TABLE 2

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

As is seen from Table 1, the maximum diameters of the pits formed under lunar conditions by explosions with E = $10^{26} - 10^{32}$ ergs fit the observed diameters of lunar craters, but are *less* than the diameters of the circular maria. But the depths at which the explosion centers should lie, in order to produce pits with these (maximum) diameters, differ considerably from the limiting depths of meteorite penetration (see Fig. 1, Table 2).

The question of the relationship between the limiting depths of meteorite penetration and the optimum depth to the explosion centers may be more expediently examined in concrete examples.

In the opinion of those advocating the meteorite hypothesis [of the lunar relief] the meteorite explosions that produced the major craters ($D \gtrsim 150$ km) and maria had energies of $10^{30} - 10^{32}$ ergs [2]. In particular, for the crater Clavius ($D = 230$ km) the energy was $E = 2.1 \cdot 10^{31}$ [8]. From graphs (Figs. 1, 2) of the relationships $W = F_1(E, V, \sigma)$ and $R = F_2(E_2, W)$ we find that the maximum meteorite penetration depth is 33 km, and consequently the radius of the explosion pit 90 km, which is much less than the size of Clavius. We could continue with a number of such examples (the craters Grimaldi, Schickard, Riccioli, Schiller and others). At the same time it should be remarked that for craters with $D < 100$ km (Tycho, Aristillus, Kepler, Bessel) there is a relationship established between the observed diameters and the maximum diameters that may be formed in meteorite explosions (with $V = 20$ km/sec, $\sigma = 8$ g/cm^3, $E = 1.07 \cdot 10^{30}$, $2.88 \cdot 10^{29}$, $5.37 \cdot 10^{28}$ and $6.31 \cdot 10^{27}$ respectively, according to ref. [8]).

The failure of agreement appears still more definitely when we look at the lunar maria. Most of the lunar maria have diameters in the range 450-600 km, while in occasional cases they are as large as 700-1000 km. The graph (Fig. 2) shows that for $E = 10^{32}$ ergs the limiting explosion-pit radius obtained under lunar conditions is 190 km. For this depth, the explosion center must be at a depth of 110 km. The calculated limiting depth of meteorite penetration with $E = 10^{32}$ is 65 km, corresponding to an explosion pit radius of 170 km, which also is much less than the sizes of the lunar maria.

Thus with explosions of energies $E = 10^{30} - 10^{31}$ ergs, no lunar craters of diameter greater than 180 km could have been formed. Similarly, explosions of energy 10^{32} ergs could not have formed the lunar maria.

The error in the approach of those who propose a meteorite explosion origin for the large craters and maria [1-5] is that they have failed to take into account the depth factor, while the characteristic crater dimension, the radius, was found, as a function of the energy, under the assumption that the explosion takes place at optimum depth. As we have shown, this assumption is erroneous.

Failure to consider the depth of the explosion center leads to other inexactitudes. It is a false conclusion that the explosions of iron and stony meteorites will cause formation of identical craters [8] if the masses and velocities are the same (that is, if the energies are the same). From Table 2 it is seen that the penetration depth of an iron meteorite is roughly twice that of a stony meteorite; it is easy to verify that for the formation of similar-sized craters the energy of a stony meteorite must be greater by about an order of magnitude than the energy of an iron meteorite (Table 2).

One must note that in all of the above calculations we have taken initial conditions such as to ensure the maximum agreement with the results deriving from the meteorite hypothesis. Furthermore in determining the maximum penetration depth of a meteorite we have assumed (following the practice of the adherents of the meteorite hypothesis) that the explosion begins after completion of the penetration. But actually the meteorite explosion begins at the moment of impact. Therefore the actual (effective) depth of the explosion center will be noticeably less than the calculated penetration depth shown in Fig. 2. Consequently the values found for the crater radii also are demonstrably too high. Knowing the propagation velocity of the detonation wave in the meteorite, one may calculate quite precisely at what depth (and at what time after impact) all the substance of the meteorite will have exploded. Consideration of this question, however, is beyond the scope of the present paper.

Thus in spite of our optimization of the initial conditions we have been unable to attain any satisfactory agreement of the experimental results with the conclusions that follow from the meteorite hypothesis. From the standpoint of the meteorite hypothesis it is not possible, within the framework of the theory of a concentrated ejective explosion, to account for the formation of the large craters and maria.

There are two directions in which we may proceed in seeking a solution to the problem of the causes responsible for the development of the large craters and maria:

1. For discussion of their formation, we may use contact charge explosion theory. Physically a contact explosion is a phenomenon closer to the explosion of a large meteorite than is an ejective explosion. But in this case it is questionable whether energy-difficulties can be surmounted, for the crater-forming effect of contact charges is less than in the case of ejective explosions.

2. The formation of the large craters and maria is due to endogenic causes.

The latter appears to be the more probable.

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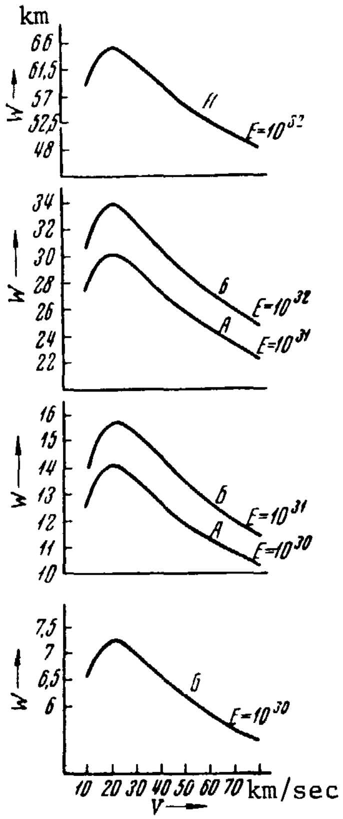

Fig.1. Relationship between penetration depth and velocity for nickel-iron (A) and stony (B) meteorites (E in ergs).

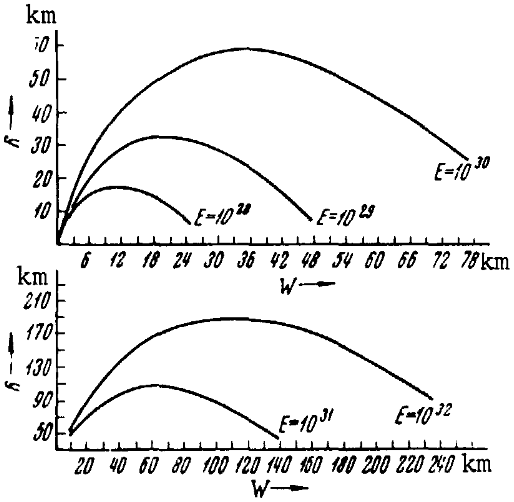

Fig.2. Dependence of radius of a lunar explosion crater on depth to explosion center and explosion energy.

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