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ON THE DISINTEGRATING ACTION OF METEORITIC IMPACTS

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SUMMARY

This is a brief review paper of the early days, concerning the action upon planets and asteroids of crater-forming meteorites. The calculations performed of critical velocities and quantity of matter lost at impact are all based upon the shock wave theory, and use is made of gas dynamics equations. These results apply to the Earth, Mars, Moon and asteroids.

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The major planets of the solar system and their satellites are continuously subject to meteoritic bombardment. The relative velocity of meteorites is rather significant and for the Earth it is measured in tens of kilometers per second. The possibility of meteoritic impact with high velocity on the Earth's surface is not excluded even despite the comparatively dense atmosphere, within which the overwhelming number of meteorites are decelerated, vaporized and pulverized. At the same time, explosive events are observed, such as funnel (crater) formation with dust and gas ejection, light and thermal effects, without omitting the formation of powerful aerial shock wave. The fall of the Tungusska meteorite on

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(*) O RAZRUSHITEL'NOM DEYSTVII METEORITNYKH UDAROV.
(**) Translated by special request in connection with the previous paper (ST-ACH-LS-10778 of 25 November 1968)

30 June 1908 [1, 2], the enormous craters, such as those of Arizona, Vabara [3, 4], Saarema [5, 6], point to the grandiose scale of these events in isolated cases. At lower scales such phenomena are apparently not so rare, as is demonstarted by the recent (12 February 1947) fall of a meteorite near Vladivostok [7].

Not being shielded by atmosphere, the surface of the Moon must be subject to much stronger action of meteorite impacts, fact to which attention was drawn by Robert Hoole, as early as in 1665. This author had proposed the hypothesis on the meteoritic origin of lunar craters [8]. A. Vegener [9], Opik [10, 11] and Wylie [12] were concerned with this question at a much later date. It was shown by one of the authors, as early as in 1937, in a work which was left unpublished, that a meteorite, colliding with the hard surface of a planet at a velocity of several tens km/sec, provokes a grandiose explosion. The action of meteorites must be particularly destructive on asteroids and on solid fragments in comet nuclei, fact to which F, Bredikhin had pointed earlier [13] and S. Orlov - at a later date [14, 16].

The explosive and destructive action during the fall of a meteorite having a high velocity singularly realizes its enormous kinetic energy. For an impact velocity > 4 to 5 km/sec, bodies behave quite analogously to a compressed gas since the molecular cohesion forces are small by comparison with their initial energy. For that reason, the events taking place during meteoritic impacts may be described by the gas dynamics equations.

A powerful shock wave propagates in planet's crust from the point of meteorite incidence, as the center of explosion, which is capable of destroying completely a solid body, within a certain volume, and transform it into a compressed gas. The total explosion energy is linked with the pressure at the bow shock wave by a relation found by L. Sedov [17] and one of the authors of [18]:

$$\varepsilon_0 = \frac{Ma^2}{2} = \frac{4\pi}{n-1}\eta p r^3. \qquad (1)$$

Here M is the mass of the meteorite, *a* is its velocity, *p* is the pressure at the bow shock wave, *r* is the distance from the incidence point, *n* is the polytropic curve index of the expanding gas, η is a parameter dependent on *n* as follows; at $n = 1, {}^7/_5, 3, 5$, η is respectively equal to ${}^1/_3, {}^1/_5, {}^1/_6, {}^1/_7$.

As follows from the work by Jensen et al [19], for strong gas densification at pressures $\sim 10^6$ kg/cm^2 $n = 3$ in a broad pressure interval.

The parameters characterizing the bow shock wave, starting from the point of incidence of the meteorite, are then given by the following basic equations of shock wave theory:

$$E = \frac{pv}{n-1} = \frac{p}{2}(v_0 - v), \tag{2}$$

$$D^2 = v_0{}^2 \frac{p}{v_0 - v}, \tag{3}$$

$$u^2 = p(v_0 - v); \tag{4}$$

E denotes the inner energy density, v is the specific volume, v_0 is the initial specific volume, D is the bow shock wave velocity, u is the gas velocity behind the wave front.

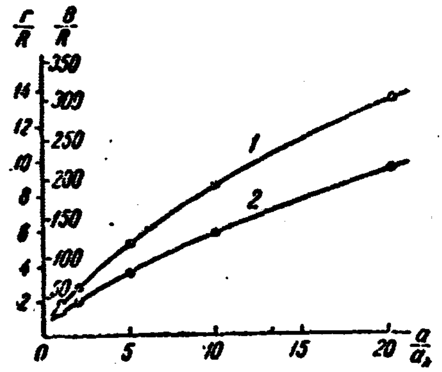

Fig.1. 1) iron meteorites, $\sigma/\rho_0=3$;
2) stone meteorites, $\sigma/\rho_0 = 1$;
$a/a_k = 5$ km.sec

The body is being disintegrated so long as the total energy at the shock wave front is

$$E + \frac{u^2}{2} = u^2 \geqslant \varepsilon_k, \tag{5}$$

where $\varepsilon_k = a_k{}^2/2$ is the corresponding disintegration energy.

Expressing v by v_0, and introducing the densities ρ and ρ_0, we find

$$\rho = \frac{n+1}{n}\rho_0 . \tag{6}$$

From (2) and (6) we find the magnitude of threshold pressure p_k, still required for the disintegration of the crystal lattice:

$$p_k = \frac{n+1}{2}\rho_0 \varepsilon_k . \tag{7}$$

Substituting (7) into (1), we shall obtain:

$$\frac{Ma^2}{2} = \frac{3}{2}\pi r^3 \rho_0 \frac{3}{2}\,\frac{n+1}{n-1}\,n\varepsilon_k , \tag{8}$$

and subsequently, introducing the radius R of the meteorite and its density σ, we obtain after small transformations:

$$\left(\frac{r}{R}\right)^3 = \frac{2}{3\eta}\,\frac{n-1}{n+1}\,\frac{\sigma}{\rho_0}\,\left(\frac{a}{a_k}\right)^2. \qquad (9)$$

The vaporization zone of the crystalline lattice $\underline{r}$, computed by formula (9), exceeds several times the radius of the meteorite, as this can easily be seen from Fig.1. When constructing the curves of Fig.1, the average earth's crust's and meteorite's composition was assumed from geochemical data.

According to Fersman [20], O, Si, Ca, Fe prevail in terrestrial crust and in stone meteorites, while iron meteorites, mostly consisting of Fe, Ni, have a density greater by about a factor of 3. Under these conditions, the ε_k of the medium is approximately 85 cal/mole, or about 3 cal/g, which corresponds to a critical velocity $a_k \simeq 5$ km/sec.

The mean energy density in the entire volume of the disintegration zone of the crystal lattice is

$$\bar{\varepsilon} = \frac{3}{2}\,\eta\,\frac{n+1}{n-1}\,\varepsilon_k, \qquad (10)$$

which, for n = 3, yields $\bar{\varepsilon} = \varepsilon_k/2$, or about 1.5 cal/g. The denotation of explosives yields an initial density of energy of 1.0 – 1.5 cal/g, so that in the disintegration zone, the entire mass of matter may be identified with an equal quantity of explssives. But it was already shown above that the volume of the disintegration zone may be tens or hundreds of times greater than the volume of the meteorite. An iron meteorite, cutting its way into terrestrial crust with a velocity of about 60 km/sec, must induce an explosive action exceeding by a factor of 1000 the effect of a quantity of explosive equalling it by weight.

At meteorite impact the explosion takes place near the very surface of the planet. The meteorite's penetration depth may be estimated from the theory of inelastic impact

$$a_x = a e^{-M_x/M}, \qquad (11)$$

where $M_x = \pi R^2 \rho_0 l$ is the mass of the medium undergoing collision with the meteorite, and a_k/a at the end of motion is conditionally assumed to be 0.01. Then

$$l = 6R\frac{\sigma}{\rho},$$

that is, it is located within the range 6 – 18 R. Consequently, the meteorite stops near the boundary of the sone of disintegration of the crystal lattice.

Experimental data of Byurlo [21] and Gauser [22] link the radius of the funnel (crater) B with the mass of explosives blasted on the surface of the soil by the following relation:

$$B^3 = km. \tag{12}$$

If B is expressed in meters and M and m in kg, we have $k \simeq 1$. From (9) and (12) we obtain

$$B^3 = \frac{2}{3\eta}\frac{n-1}{n+1}\left(\frac{a}{a_k}\right)^2 M. \tag{13}$$

Assuming n = 3, we find that

$$B^3 = 2\left(\frac{a}{a_k}\right)^2 M. \tag{14}$$

Since $(a/a_k)^2$ may vary in probable limits from 1 to 200, we may conclude that the Arizona crater of 1200 m in diameter could have been formed by the fall of meteorite having a mass $\leqslant$ 100,000 tons if the meteorite was on "spent flight", i.e., if it had a velocity $a \simeq a_k$, and probably not less than 500 tons. Therefore, the Arizona meteorite could have been an iron fragment with diameter of the order of 5 – 30 m (see Fig.1).

The mean velocity of masses ejected at meteoritic explosion and having properties of a gas, was estimated from the theory of nonstationary processes [23], which in the case under consideration is 3 km/sec. At the same time, the distribution of velocities will be such that one half of all masses will be imparted a velocity > 3 km/sec, ten percent (10%) – above 5 km/sec, and separate particles – even to 2a.

If a = 50 km/sec, a substantial part of matter will be imparted velocities above the critical and will be ejected into the interplanetary space. Disregarding the braking action of the atmosphere, which obviously is quite great for the Earth, the planet will lose (see Table 1):

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TABLE 1

PLANET	EARTH	MARS	MOON	ASTEROID
Critical velocity, km/sec....	11.2	5.0	2.4	0.5
Relative quantity of lost mass (M - 1)	2	20	200	4000

Being devoid of atmosphere, the Moon and the asteroids daily lose a mass which exceeds by hundreds and thousands times the mass of meteorites falling from them. Assuming the very areful estimate by Watson [24], 1 ton of meteoric matter falls daily on Earth. Since the Moon is for meteorites a target 13 times smaller by area than the Earth, it must lose daily a mass of the order of 15 tons. The smaller the planet, satellite or asteroid dimensions, the more intense their disintegration process. Quite posiible are catastrophic cases of total destruction of microplanets or hard particles in cometary nuclei, for the relative orbital velocities of solar system's bodies in its inner part have magnitudes of tens km/sec (the corresponding computation shows that for an impact velocity of 50 km per sec, the mass of a totally destructed asteroid may exceed by 10,000 times the mass of the incident meteorite). Consequently, the meteritic bombardment and the disintegration pf planetary and cometary matter induced by it in the solar system must be accounted for as important cosmogonic factors.

Let us note in conclusion that crater-forming meteorites, approaching the Earth's surface with high velocity, generate a powerful shock wave in air also. The pressure at its leading edge is 25,000 kg/cm at a = 50 km/sec. Such an aerial shock wave carries out destructions along the meteorite's trajectpry projection on the ground even during flight of the meteorite and sometimes at significant distances from the place of fall.

*** THE END ***

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