ON THE VELOCITY AND ENERGY OF THE TUNGUSKA METEORITE

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Abstract

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The study of the region of destruction caused by the fall of the Tunguska meteorite on 30 VI 1908 (⁀1), and calculations of the parameters of the shock wave formed during its flight through the atmosphere (⁀2), made it possible to estimate the total energy of destruction at $\sim 10^{23}$ ergs. The clear picture of the radial fall of the forest from the epicenter indicates the predominant action of the blast wave, while the very character of the fall, in particular the existence of a "zone of indifference" and standing tree trunks ("telegraph poles"), indicates beyond doubt that the explosion of the meteorite occurred in the air (⁀1). This thereby confirms the assumption of the above-ground character of the explosion, expressed as early as 1925 by A. V. Voznesensky and somewhat later by L. A. Kulik (⁀3). Possible causes of the explosion will be considered below.

The motion of the meteorite in the atmosphere was considered by V. A. Bronshten (⁀4) on the basis of the well-known equations of meteor physics (⁀5, ⁀6). Solutions were obtained for the range of initial masses 10^5–10^7 tons, initial velocities 11–46 km/sec, and values of the drag coefficient $c_x/2 = 0.5 \div 2$.

From the values of the final masses and velocities for the entire family of solutions, values of the kinetic energy of the meteorite E_k were calculated. Comparison of the obtained values of E_k with the above estimates of the energy of destruction shows that the initial mass of the meteorite in any case exceeded 10^5 tons and was apparently within the range 10^6–10^7 tons, which agrees well in order of magnitude with V. G. Fesenkov' s estimate, made on the basis of entirely different considerations (⁀8).

Regardless of the adopted value of the initial mass, the final velocity and mass of the meteorite must lie within the limits: $16 < v_k < 30$ km/sec, $2 \cdot 10^4 < M_k < 7.5 \cdot 10^4$ tons. The physical meaning of the independence of these estimates from M_0 is that, in order to reconcile the value of E_k with the data on the energy of destruction in the region of the fall ([1],2), when increasing the estimate of M_0 one must simultaneously increase the adopted value of the drag coefficient c_x, i.e., assume that a larger mass experiences greater resistance in the atmosphere. Ceplecha' s study (⁀7) of the Příbram meteorite showed that for a large meteoric body $c_x/2 = 0.43$, and therefore the most probable solution is the variant corresponding to $M_0 = 10^6$ tons, $v_0 = 35 \div 43$ km/sec, $v_k = 30$

km/sec, $M_k = 2 \cdot 10^4$ tons.

Let us now turn to the physical investigation of the phenomena accompanying the flight of a large meteoric body in the Earth' s atmosphere.

During motion with cosmic velocity, a body of diameter 25–30 m will already at an altitude of 120 km begin to form a shock wave, the temperature at whose front T_y^0 in the ideal case is determined by the relation

$$\frac{c_v}{\mu} T_y^0 = \frac{v^2}{2}, \tag{1}$$

where c_v is the heat capacity of air (per mole), and μ is its molecular weight ($\mu = 29$).

A more exact formula for T_y^0, taking into account the change in the adiabatic exponent $\gamma = c_p/c_v$, has the form ([9])

$$T_y^0 = T_1 \frac{p_2}{p_1} \frac{\rho_1}{\rho_2} = T_1 \frac{p_2}{p_1} \frac{\gamma - 1}{\gamma + 1}, \tag{2}$$

where $p_{1,2}$ and $\rho_{1,2}$ are the pressure and density of the air, respectively, before and behind the shock-wave front, and T_1 is the temperature before the front.

In the real case, the temperature at the shock-wave front T_y will be less than T_y^0 because of energy losses to dissociation and ionization of the gas ([10]). Values of T_y^0 and T_y for different meteorite velocities are given in Table 1.

Table 1

v, km/sec	12	20	30	40	50	60	70
T_y^0, degrees, by (1)	51 600	145 000	319 000	565 000	890 000	1 305 000	1 800 000
T_y^0, degrees, by (2)	45 700	139 000	330 000	589 000	940 000	1 400 000	1 970 000
T_y, degrees, by ([10])	20 300	40 700	70 800	99 000	129 000	162 000	203 000

Thus, the temperature at the shock-wave front of the Tunguska meteorite was $70\,000 \div 100\,000^\circ$. The transition from T_y^0, determined by formula (1), to the real temperature T_y can be carried out by the empirical formula

$$T_y = \eta T_y^0 v^{-0.7}, \tag{3}$$

where $\eta = 2.27$.

The radiation energy of the shock wave is

$$E_{iy} = \sigma S_{iT} y^4, \tag{4}$$

where σ is the Stefan–Boltzmann constant, and S_i is the radiating area of the shock wave. It may be assumed that $S_i = \beta S_m$, where S_m is the area of the meteorite, which in first approximation we take to be spherical; $\beta = 5 \div 10$. Since

$$S_m = 4\pi \left(\frac{3}{4\pi}\frac{M}{\delta}\right)^{2/3} = 4\pi \left(\frac{3}{2\pi}\frac{E_m}{\delta v^2}\right)^{2/3}, \tag{5}$$

then, substituting (1), (3), and (5) into (4), we obtain

$$E_i = \beta\sigma \frac{\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\left(\frac{\mu\eta}{c_v}\right)^4\left(\frac{E_m}{\delta}\right)^{2/3} v^{3.9}. \tag{6}$$

Here E_m is the total energy of the flying meteorite, and δ is its density. For a given energy E_m, the radiation energy increases directly in proportion to the fourth power of the velocity.

In this connection it is necessary to note the erroneous nature of A. V. Zolotov' s calculations ([11]), who took the color temperature of the bolide (upper limit 6000°) for the temperature of the shock wave and tried from this to calculate the velocity of the flying body by formula (1). It should be borne in mind that the radiation maximum at $T_y = 70\,000^\circ$ lies in the ultraviolet part of the spectrum. For such radiation, air is practically opaque. However, ahead of the shock-wave front there arises a heated zone with a radiating area much larger than the radiating area of the shock wave. Re-emission occurs in this case, and the temperature of the outer zone will be lower than T_y, while its radiation will shift into the visible part of the spectrum. Part of this radiation is perceived by the eye as the yellow color of the bolide. Thus, it is obvious that A. V. Zolotov' s attempt to determine the temperature of the shock wave from the color of the bolide is untenable, and calculating the velocity of the meteoric body from this temperature is meaningless.

The use by A. V. Zolotov of the formula relating the luminous energy of the explosion E_c and the luminous impulse I_c is likewise unfounded:

Fig. 1. Energy balance during the motion of an iron meteoric body: 1 –total energy input (iron, $v_0 = 60$ km/sec, $i = 72^\circ$, $r_0 = 10^2$ cm); 2 –energy input from the shock wave due to radiation; 3 –energy input due to flow around the body; 4 –energy expenditure on evaporation

Figure 1: Fig. 1. Energy balance during the motion of an iron meteoric body: 1 –total energy input (iron, $v_0 = 60$ km/sec, $i = 72^\circ$, $r_0 = 10^2$ cm); 2 –energy input from the shock wave due to radiation; 3 –energy input due to flow around the body; 4 –energy expenditure on evaporation

$$E_c = \frac{I_c \cdot 4\pi R^2}{e^{-\mu(R-r)}}; \tag{7}$$

where R is the distance from the explosion site, r is the radius of the luminous region, and μ is the coefficient of light absorption in the atmosphere. The latter was taken to be 0.033 km^{-1}, which corresponds to an unusually high transparency coefficient $p = 0.93$, quite uncharacteristic of taiga regions. If, however, one takes the more realistic, though still high, value $p = 0.80$, then we obtain $\mu = 0.1$ km^{-1}, and all of A. V. Zolotov' s estimates change by several orders of magnitude.

Let us conclude by considering the probable nature of the explosion of the Tunguska meteorite. The general equation for the thermal balance of a meteorite has the form [10]

$$\left(\Lambda \frac{\rho v^3}{2} + W \quad \right) S\, dt = E \quad + \sigma \left(T^4 - T_a^4\right) S_m\, dt + QmNS_m\, dt, \tag{8}$$

where W is the flux density of radiation from the shock wave; E is the part of the energy going into heating the body; T and T_a are the temperatures of the meteorite and of the atmosphere; S is the midsection area; S_m is the surface of the body; Q is the heat of evaporation; N is the number of evaporating molecules (cm$^{-2} \cdot$ sec^{-1}); m is the mass of a molecule.

Analysis of equation (8) shows that the second term on the left-hand side, due to radiation, is much larger than the first, due to heat transfer in flow. The expenditure of heat on evaporation (the third term on the right-hand side) rapidly becomes much larger than the expenditure of heat on radiation from the surface of the meteoric body (the second term), and therefore it is sufficient to consider the supply of heat due to radiation from the shock-wave front and the expenditure of heat on evaporation. Their dependence on altitude is shown for an iron meteorite in Fig. 1.

Fig. 1. Energy balance during the motion of an iron meteoric body:
1 –total energy input (iron, $v_0 = 60$ km/sec, $i = 72^\circ$, $r_0 = 10^2$ cm);
2 –energy input from the shock wave due to radiation;

3 –energy input due to flow around the body;
4 –energy expenditure on evaporation.

As can be seen from Fig. 1, at a certain altitude $h = 18$ km the supply and expenditure of heat become equal, heating ceases, after which the body begins to cool and, while simultaneously braking, reaches the surface of the Earth. A similar picture will hold for a stony meteorite.

But if we imagine that we are dealing with the nucleus of a small comet, as I. S. Astapovich and Whipple once supposed, and assume that this body, like all comet nuclei, is a conglomerate of methane-ammonia ices also containing stone blocks and dust, then the picture of the phenomena will be different. Namely, for an icy block with $r = 10^3$ cm, $v = 60$ km/sec, $i = 72°$, at an altitude of 50 km the energy going into evaporation is an order of magnitude less than the energy received by the body from the shock wave. As a result, the body is strongly heated in depth and evaporates ever faster, i.e., the boundary of the evaporated layer moves ever faster toward the center. In a comparatively short time (~ 0.2 sec) a significant mass of material evaporates (about 30%). If the process proceeds sufficiently rapidly, then the evaporated particles,

flying apart, can create a strong spherical shock wave, and the phenomenon will have the character of an extended explosion.

At a velocity $v = 30$ km/sec the power of the process ($2 \cdot 10^{13}$ erg/g • sec) is comparable with the explosion of gunpowder (10^{13} erg/g • sec). Such a phenomenon, studied in greater detail by K. P. Stanyukovich and V. P. Shalimov [12], may be called a "thermal explosion."

We have considered above a mechanism that can lead to an explosion when a single body enters the atmosphere. However, there is also another possible point of view on the structure of cometary nuclei. Thus, V. G. Fesenkov regards the nucleus of a comet as a dense swarm of comparatively small bodies.

Analysis of the directions of tree fall clearly indicates the presence not of one, but of several centers of fall, to which L. A. Kulik had already drawn attention. Taking this into account, V. G. Fesenkov proposed [13] yet another possible mechanism of destruction under the action of the entry of a cometary nucleus, which the Tunguska meteorite undoubtedly was.

When a sufficiently dense swarm of bodies enters the Earth' s atmosphere with cosmic velocity, the swarm may be surrounded by a common shock wave. However, as it penetrates into the lower layers of the atmosphere, owing to differences in mass and, hence, in deceleration, the density of the swarm must decrease, and its transverse dimensions and "length" increase. As a result, each individual body, or group of bodies close in mass, will possess individual shock waves. In this case the process of destruction of the swarm bodies will end even before they reach the Earth' s surface (because of the increase of surface area per unit mass), while the shock waves, on reaching the Earth, will cause all the observed destruction, and the radiation of the powerful shock wave will produce radiant burns on a number of objects and, in particular, on trees.

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