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Abstract

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ON THE QUESTION OF THE POSSIBILITY OF A "THERMAL" EXPLOSION AND THE STRUCTURE OF THE TUNGUSKA COSMIC BODY

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In recent years, several different and contradictory assumptions have been put forward concerning the structure, density, and dimensions of the Tunguska cosmic body. Some authors believe that it was a loose snow-like body; others have taken the cosmic body to be a monolithic block of ice, stone, or iron ([1,2]). Some authors are developing the hypothesis that the Tunguska cosmic body was a swarm of particles constituting the head of a comet, or a dust cloud with density $\rho_t \ll 1$ g/cm^3 and a cross section of several square kilometers ([3,4]). However, the problem of the motion in the atmosphere of a swarm of particles or a dust cloud with density $\rho_t \ll 1$ has still not been solved.

The hypotheses listed above are based on the assumption that the explosion of the cosmic body and all the destruction in the taiga occurred at the expense of the kinetic energy of the body itself, moving at a speed of not less than 30 km per second ([1,5]). Proceeding from this, in determining the parameters of the cosmic body, besides the equations of meteor physics, works ([2]) and ([5]) used only one relation:

$$E_p \ll E_k = \frac{m_k v_k^2}{2}; \quad (1)$$

relating the total energy E_p released in the catastrophe, the final mass m_k, and the velocity v_k of the cosmic body to its kinetic energy E_k. However, with respect to the parameters of the cosmic body, the equations of meteor physics and condition (1) do not have a unique solution ([2]).

In the present article, in order to determine the specific parameters of the Tunguska cosmic body, an additional connection is used between the velocity and dimensions of the flying body, for a known power of the ballistic wave, which is determined from factual data on the forest fall in the region of the Tunguska catastrophe of 1908.

One of the basic facts is the radial fall of the forest in the region of the Tunguska catastrophe, with a practically single center (Fig. 1), over an area of

Fig. 1. Diagram of the area of fallen forest in the region of the Tunguska catastrophe of 1908. AB is the axis of symmetry

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about 2000 km^2 ([6]), with a mean radius of the region of 25 km. The presence of standing forest, which remained on the root after the catastrophe and was located inside the region of radially felled forest ([7]), indicates that the center of the shock wave was in the air at some height above the Earth' s surface, not less than 5 km ([8]).

From experimental data it is known that the alignment of the shock wave from the explosion of a cylindrical charge of finite dimensions occurs at a distance several times greater than the linear dimensions of the charge. In the Tunguska case, with the length of the final active segment of the trajectory of the cosmic body being 25-30 km (Fig. 1), which corresponds to the length of an equivalent cylindrical explosion, with a small inclination of the trajectory ($\varphi = 5$–$17°$ ([7])) and with a flight altitude on the final segment of 5-10 km, alignment of the ballistic wave and its action like a spherical wave within the region of destruction is impossible.

From all that has been said, one may conclude that, under the conditions of the Tunguska catastrophe, the radial fall of the forest was produced by an explosive spherical wave. Therefore the energy of the shock wave that produced the radial fall of the forest in the taiga may quite justifiably be calculated according to the laws of a spherical explosion. As the height of the explosion changes from 5 to 10 km, the energy required for the observed destruction changes from $(3 \pm 1) \cdot 10^{23}$ to $(5.5 \pm 1.5) \cdot 10^{23}$ erg. From the radial character of the forest fall and the absence of an osesymmetric relative to the trajectory strip of forest fall (Fig. 1), it follows that the power of the ballistic wave was less than the power of the explosive wave and was insufficient to produce the forest fall.

Fig. 1. Diagram of the area of fallen forest in the region of the Tunguska catastrophe of 1908. AB is the axis of symmetry.

Thus, throughout the entire region of destruction in the taiga, including the zone of maximum action, which is located in the region of irregular reflection of the ballistic wave from the Earth' s surface at a distance from the projection of the trajectory equal to the flight altitude of the body, the excess pressure at the front of the ballistic wave ΔP_{b} is less than the excess pressure at the front of the explosive wave ΔP_{v}. From experimental data on large explosions it is known that the excess pressure at the front of a shock wave that fells trees is equal to 0.1-0.14 kgf/cm^2 ([9]). Taking into account that in the region of irregular reflection, in which the pressure of the shock wave increases by not less than a factor of 2 ([10,11]), for a directly incident ballistic wave at a distance $r_2 = \sqrt{2H}$ (where H is the height of the explosion of the cosmic body) from the final segment of the trajectory, the inequality holds

$$\Delta P_{\mathrm{b}} \leq 0.05 \text{ kgf/cm}^2. \tag{2}$$

It is known that the pressure at the front of a direct ballistic wave can be calculated from formulas for a cylindrical explosion equivalent to the action of the ballistic wave ([12]):

$$\frac{\Delta P_{\mathrm{b}}}{\overline{P}_1} = \frac{4\gamma}{(\gamma+1)\left(\sqrt{16\sqrt{2}\,\gamma\alpha_2 R_2^{3/2}+1}-1\right)}, \qquad 2 \leq R_2 < \infty, \tag{3}$$

where $R_2 = r_2/r_0$ is a dimensionless parameter, r_2 is the radius of the shock wave in meters, $r_0 = \sqrt{E_0/\overline{P}_1}$ is the dynamic length of the cylindrical explosion in m, E_0 is the explosion energy per unit length in kgm; $\overline{P}_1$ is the mean value of the pressure in kgf/cm^2 in the lower layer of the atmosphere of thickness equal to the explosion height, γ is Poisson' s adiabatic exponent, $\alpha_2 = 0.983$ is a constant multiplier.

The relation between the diameter d of the effective cross section of a body flying with supersonic velocity v and forming a ballistic wave, and the characteristic parameter of the equivalent cylindrical

the explosion is expressed by the formula

$$r_0 = \sqrt{\frac{c_x\gamma}{2}}\,Md, \tag{4}$$

where c_x is the drag coefficient, $M = v/a_1$ is the Mach number, and a_1 is the speed of sound in air.

It follows from equations (3) and (4) that the value of the dynamic length of the equivalent cylindrical explosion r_0 completely and unambiguously characterizes the parameters of the cosmic body and of the ballistic wave formed by the flight of this body in the atmosphere.

Figure 2 gives the maximum values of the diameter of the cosmic body as a function of its flight speed, calculated from formulas (3) and (4) and condition (2), for the minimum (at a speed $v > 1$ km/sec) value $c_x = 0.92$ and for three values of H: 5, 7, and 10 km (Fig. 2, curves 1-3).

If it is assumed that all the destruction in the taiga was produced at the expense of the kinetic energy of the flying cosmic body, then from formulas (3), (4), and relation (1) we find the minimum values of the possible density ρ_{t} of the cosmic body

Fig. 2

Figure 2: Fig. 2

$$\rho_{\text{t}} = 6.86 \cdot 10^{-2} c_x^{3/2} \frac{E_{\text{k}}}{r_2^3 a_1^3} \left(\frac{\Delta P}{\overline{P}_1}\right)^{-4} v, \tag{5}$$

where $\overline{P}_1$ and $\overline{a}_1$ are the mean values of the pressure and the speed of sound in the lower atmospheric layer of thickness equal to the height of the explosion.

Fig. 2. Dependence of the diameter (1-3) and density (4-7) of the cosmic body on speed for $H = 5$ km (1), $H = 7$ km (2), $H = 10$ km (3), 4—$H = 10$ km, $E_{\text{k}} = 4 \cdot 10^{23}$ erg; 5—$H = 7$ km, $E_{\text{k}} = 2.5 \cdot 10^{23}$ erg; 6—$H = 7$ km, $E_{\text{k}} = 4 \cdot 10^{23}$ erg; 7—$H = 5$ km, $E_{\text{k}} = 2 \cdot 10^{23}$ erg.

The curves of the dependence of the minimum possible density of the cosmic body on its speed, calculated from formula (5) and condition (2) (Fig. 2), show that even at the limiting extreme values of the parameters, at a speed of 30 km/sec the diameter of the Tunguska cosmic body cannot be greater than 23 m (curve 3), and the corresponding density of the body cannot be less than 13 g/cm^3 (curve 4). With such dimensions and density, the Tunguska cosmic body apparently could not have been a swarm of particles or a cloud of cosmic dust.

The curves in Fig. 2 also show that for real icy, stony, and iron bodies ($\rho_{\text{t}} = 1$; 3 and 7.8 g/cm^3) in the Tunguska case, at an explosion height $H = 7$ km, the speed could not have exceeded 0.6; 2, and 5 km/sec, respectively (Fig. 2, curve 5). But at such a low speed, an explosion of a cosmic body in the air at the expense of its kinetic energy is fundamentally impossible.

A necessary condition for a "thermal" explosion of a cosmic body in the air at the expense of its kinetic energy is a high cosmic speed of the body, no less than 30 km/sec (1, 5), which for the Tunguska cosmic body has so far remained only an assumption. In addition, the theoretical calculations of the process of heating of a cosmic body during flight in work (1) are based on the assumption that 0.1–0.01 of the energy of radiation of the bal-

listic shock wave. According to a remark by B. P. Konstantinov*, this calculation does not take into account the hydrodynamic effect in the transfer of radiant energy from the ballistic wave to the evaporating surface of the body, which may change the results of the calculation by several orders of magnitude. Thus, at present a "thermal" explosion of a cosmic body in the air does not have sufficient physical and theoretical justification.

Let us consider this question from a somewhat different side. Let us calculate the energy and possible destruction caused by the ballistic wave under the conditions of a hypothetical thermal explosion, which were not taken into account in work ([1]).

Table 1

Basic parameters of the ballistic wave of a cosmic body under the conditions of the Tunguska catastrophe in a thermal explosion.

$H = 10$ km; $\overline{P}_1 = 0.563$ kg/cm^2; $E_k = 4 \cdot 10^{23}$ erg, $v_k = 30$ km/sec;
$\overline{a}_1 = 320$ m/sec; $M = 94$; $\Delta P_\delta = 0.05$ kg/cm^2; $l = 30$ km;
$m_k = 8.9 \cdot 10^4$ t, $R_2 = 8.2$

Substance	ρ_T, g/cm^3	d, m	c_x	r_0, m	E_0, erg/cm	$E_b = E_0 l$, erg	r_2, km
Ice	1	55	1	4300	$1 \cdot 10^{17}$	$3 \cdot 10^{23}$	35
Ice	1	55	2	6000	$2 \cdot 10^{17}$	$6 \cdot 10^{23}$	50
Ice	1	55	3.6	8300	$4 \cdot 10^{17}$	$1.2 \cdot 10^{24}$	68
Stone	3	37	1	2900	$4.6 \cdot 10^{16}$	$1.4 \cdot 10^{23}$	24
Stone	3	37	2	4100	$9.3 \cdot 10^{16}$	$2.8 \cdot 10^{23}$	34
Iron	7.8	28	1	2200	$2.7 \cdot 10^{16}$	$8.1 \cdot 10^{22}$	18
Iron	7.8	28	2	3100	$5.3 \cdot 10^{16}$	$1.6 \cdot 10^{23}$	25

Under the conditions of the Tunguska catastrophe, the length l of the active terminal segment of the trajectory is about 30 km (Fig. 1), and the extent of the presumed thermal explosion is about 6 km ([1]); therefore, in the Tunguska case, in a thermal explosion there should be areas of destruction separately by the explosive and ballistic waves.

Table 1 gives the basic parameters of the ballistic wave and the dimensions r_2 of the area of forest fall caused by the ballistic wave during flight in the atmosphere at a velocity $v = 30$ km/sec of icy, stony, and iron cosmic bodies, calculated from formulas (1), (3), (4). It is seen from Table 1 that, under the conditions of the Tunguska catastrophe, a necessary condition for a "thermal explosion" of a cosmic body in the air (for a body density $\rho_T \leq 8$ g/cm^3) is the commensurability of the power of the explosive and ballistic waves $E_k \approx E_b$, and the commensurability of the zones of destruction by the explosive and ballistic waves; in connection with this, there should be an axisymmetric (relative to the trajectory) band-like forest fall, which is not observed in reality.

Thus, we obtain the somewhat paradoxical conclusion that, from the point of view of a "thermal" explosion of a cosmic body in the air, a "thermal" explosion of an ordinary cosmic body with density $\rho_T \leq 8$ g/cm^3 at the expense of its kinetic energy is impossible in the Tunguska case.

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CITED LITERATURE

[1] K. P. Stanyukovich, V. P. Shalimov, *Meteoritika*, issue 20, 54 (1960).
[2] V. A. Bronshten, *Meteoritika*, issue 20, 72 (1960).
[3] V. G. Fesenkov, *Meteoritika*, issue 21, 3 (1961).
[4] G. F. Plekhanov et al., *Geology and Geophysics*, No. 1, 111 (1963).
[5] K. P. Stanyukovich, V. A. Bronshten, *DAN*, 140, No. 3, 583 (1961).
[6] K. P. Florensky, *Geochemistry*, No. 3 (1963).
[7] E. L. Krinov, *The Tunguska Meteorite*, Publ. House of the Academy of Sciences of the USSR, 1949.
[8] A. V. Zolotov, *DAN*, 136, No. 1, 84 (1961).
[9] M. Grodz, V. Ya. Kovkin, *Atomic Weapons and Anti-Atomic Protection*, Moscow, 1958.
[10] Yu. S. Yakovlev, *Hydrodynamics of Explosion*, 1961.
[11] A. P. Glushko et al., *Atomic Weapons and Anti-Atomic Protection*, 1958.
[12] V. P. Korobeinikov et al., *Theory of a Point Explosion*, 1961.

* At the discussion of the report by K. P. Stanyukovich at the 10th Meteorite Conference, June 1–4, 1962, in Leningrad.

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