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A. V. ZOLOTOV

ESTIMATION OF THE PARAMETERS OF THE TUNGUSKA COSMIC BODY FROM NEW DATA

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This article gives an estimate of the parameters of the Tunguska cosmic body, based on an analysis of the map of felled forest in the region of the Tunguska catastrophe of 1908, constructed from new data of the 1961 expedition of the Committee on Meteorites of the USSR Academy of Sciences ([1]), and on an analysis of the interaction of the explosive and ballistic waves that arose during the flight and explosion of the cosmic body.

In ([2]) an approximate estimate is given of the parameters of the Tunguska cosmic body, based on the assumption that the destruction in the taiga was produced by a ballistic wave. However, the actual data on the felling of the forest in the taiga do not confirm this assumption. In ([3]) it is shown that, under the conditions of the Tunguska catastrophe, with a small inclination of the trajectory to the Earth' s surface ($\varphi = 5$–17°) and a low flight altitude of the body on the final segment of the trajectory ($h = 5$–10 km), in comparison with the dimensions of the region of destruction ($R = 25$–30 km), the radial felling of the forest was produced by an explosive spherical shock wave. The fact of forest felling by an explosive wave is also noted in ([4]).

Thus, the parameters and motion of the shock wave of the Tunguska explosion may be considered according to the basic laws of motion of the wave of a spherical explosion ([5]):

$$\frac{\Delta P_\text{v}}{P_1} = \frac{4\gamma}{\gamma+1} \cdot \frac{1}{\sqrt{1+50\gamma\alpha_1 R_2^2\left[\ln\frac{R_2}{2}+1\right]}-1}, \quad 2 \leqslant R_2 < \infty; \qquad (1)$$

$$\tau = \frac{R_2}{\sqrt{\gamma}} - \frac{0.4}{\sqrt{2}\sqrt{\alpha_1\gamma}}\sqrt{\ln\frac{R_2}{0.735}} - 0.22, \qquad (2)$$

where ΔP_v is the excess pressure at the front of the explosive shock wave; $R_2 = r_2/r_0$ is a dimensionless parameter; r_2 is the radius of the shock wave in meters; $r_0 = \sqrt[3]{E_0/\overline{P}_1}$ is the dynamic length of the spherical explosion in meters; E_0 is the explosion energy in kgm; $\overline{P}_1$ is the mean pressure value in kg/cm^2 in the lower atmospheric layer of thickness equal to the explosion height H; γ is Poisson' s adiabatic exponent; $\alpha_1 = 0.851$ is a constant multiplier; τ is dimensionless time.

The mean radius of the region of felled forest is 25 km (Fig. 1). From experimental data on large explosions it is known that the excess pressure at the front of a shock wave that fells trees is 0.12 ± 0.02 kg/cm^2 ([6]). Taking into account that in the region of irregular reflection, in which the pressure at the shock-wave front increases by no less than a factor of 2 ([7,8]), the excess pressure ΔP_{v} at the front of the direct incident wave at the boundary of forest felling at a distance of 25 km from the epicenter will be 0.06 ± 0.01 kg/cm^2. From the known pressure at the front of a spherical shock wave at one point, according to equation (1), the basic parameters of the wave are uniquely determined throughout space, including the explosion energy, which is also uniquely determined (Table 1).

The basic parameters of the ballistic wave of the cosmic body can, with a known degree of approximation, be calculated from the formulas ([3,5]):

$$\Delta P_{\text{b}} = f_1(R_2), \tag{3}$$

$$\tau = f_2(R_2). \tag{4}$$

Table 1

Parameters of the shock wave of the Tunguska explosion of 1908 at a distance of 25 km from the epicenter for different explosion heights

H, km	ΔP_{v}, kg/cm^2	$\overline{P}_1$, kg/cm^2	R_2	τ	r_2, m	r_0, m	$E_0 = r_0^3\overline{P}_1$, erg	$t_0^* = r_0\sqrt{\frac{\overline{\rho}_1}{\overline{P}_1}}$, sec.	$t_{\text{v}} = t_0\tau$, sec.
5	0.06	0.75	3.34	2.28	25500	7650	$3.3 \cdot 10^{23}$	27.5	62.6
7	0.06	0.665	3.06	2.05	26000	8510	$4.0 \cdot 10^{23}$	30.9	63.3
10	0.06	0.563	2.75	1.80	27000	9820	$5.2 \cdot 10^{23}$	36.1	65.0

* t_0 –dynamic time.

Obviously, by the moment of the body' s explosion the ballistic wave had already been formed; therefore, after the explosion there occurred an encounter and crossing of the fronts of both shock waves, during which the initial direction of their motion must have changed ([9,10]). It follows from this that the interaction of the explosive and ballistic waves in the felling of the forest should have manifested itself as a deviation of the directions of the fallen trees from the epicenter, i.e., as a violation of cylindrical symmetry and a deviation of the forest fall from strict radiality. Indeed, such a deviation of the directions of the fallen trees from the epicenter is observed in the Tunguska catastrophe (Fig. 1).

In zones 1, 2, and 3 (Fig. 1) a clear pattern of cylindrical symmetry is observed (the predominance of circles), i.e., a pattern of exact radial fall; in zones 4 and 5 a noticeable deviation of the arrows from the epicenter is observed. The deviations of the arrows in these zones are arranged symmetrically with respect to the line AB, which is the axis of symmetry of the entire destruction zone and which, apparently, may be taken as the projection of the trajectory of the cosmic body over the final segment of its flight.

A statistical analysis of the directions of all fallen trees shows that the deviation of the arrows from the epicenter in zones 4 and 5 (Fig. 1) is systematic and goes far beyond the limits of the root-mean-square error, determined by an ellipse of deviations with semiaxes of 1 and 1.5 km ([11]). Each arrow in Fig. 1 corresponds to the mean direction of about 100 fallen trees ([1]), which ensures the reliability of the results of processing the map of the fallen forest. From the angle of deflection of the explosive wave at the points of intersection with the front of the ballistic wave (in our case at the boundary of zones 1 and 4, 2 and 5—Fig. 1), one can estimate the quantitative ratio of the intensities of the explosive and ballistic waves ([10]):

$$\frac{\Delta P_{\text{b}}}{\Delta P_{\text{v}}} = \frac{\psi_1}{\psi - \psi_1} = \frac{\psi_1}{\psi_2}. \tag{5}$$

Since after the explosion an intersection in space of the explosive and ballistic waves took place, in principle it is possible to determine the position of the line of intersection of these waves on the Earth' s surface. In a first approximation this line corresponds to the boundary between zones 1 and 4 and zones 2 and 5 (Fig. 1, lines OP and OQ). The mean angle of deviation of the direction of fallen trees from the epicenter in zones 4 and 5 in the vicinity of the lines of intersection of the shock waves OP and OQ is 8°. Then, in order to determine the ratio of the overpressures at the fronts of the shock waves at the point of intersection according to formula (5), it is necessary to determine the Mach angle α and the initial direction of motion of the ballistic wave.

The set of points of intersection of the explosive and ballistic waves is the set of points of simultaneous arrival of both waves at these points. Hence, for point P we have $t_{\sigma} = t_{\text{T}} + t_{\text{v}}$, where t_{σ} is the time of motion of the ballistic wave from the trajectory (from point N') to point P; t_{T} is the time of motion of the cosmic body from point N' to the point of explosion O; t_{v} is the time of motion of the explosive wave from the point of explosion O' to point P.

Figure 1. Diagram of destruction in the region of the Tunguska catastrophe of 1908

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Fig. 1. Diagram of destruction in the region of the Tunguska catastrophe of 1908. **1-3** –region of strictly radial forest fall by a spherical explosive wave; **4-5** –regions of the combined action of the explosive and ballistic waves; **6** –front of the explosive wave; **7** –front of the ballistic wave at the moment of explosion; **8** –front of the ballistic wave at the moment of encounter with the explosive wave at point P, at a distance of 25 km from the epicenter of the explosion; **9** –boundary of the region of fallen forest (after K. P. Florenskii); **10** –trajectory of the cosmic body (after E. L. Krinov); **11-12** –fallen trees whose direction passes through the epicenter of the explosion and corresponds to spherical symmetry; **13** –directions of fallen trees that deviate from the epicenter chaotically; **14** –directions of "fallen" trees that deviate from the epicenter and correspond to axial symmetry; **15** –directions of motion of the shock wave at point P_1; **16-27** –successive positions of the explosive-wave front every 5 s after the explosion; **28** –boundary between regions with strictly radial (1; 2) and axisymmetric (4; 5) forest fall; **29** –calculated line of intersection of the explosive and ballistic waves at successive moments of time.

Determining the time for a shock wave to travel a known distance when the parameters of the wave are known is a problem solved for all types of waves (5). Then, for a specific point P located near the line of intersection of the shock waves at a distance of 25 km from the epicenter, using the known angle of deviation ($\omega = 8°$) of the explosive shock wave from its initial direction, by the method of successive approximations according to formulas (1)–(5) and the condition $\Delta P_{\text{B}} = 0.06 \pm 0.01$ kgf/cm^2, using the relation between the angle α and the velocity of the cosmic body v, $\sin\alpha = c/v$, where c is the velocity of the ballistic wave, one can determine the time of travel of the explosive and ballistic waves to point P, the angle α, and the initial direction of motion of the ballistic wave, the ratio of the excess pressures at the fronts of the explosive and ballistic waves at point P, as well as

Table 2

Calculated data for determining the parameters of the Tunguska cosmic body by the method of successive approximations

Initial data: $h = 10$ km, $\bar{P}_1 = 0.563$ kg/cm^2, $R = 25$ km, $\Delta P_{\text{v}} = 0.06$ kg/cm^2, $t_{\text{v}} = 63.3$ sec, $\psi_1 = \omega/2 = 4°$, $v = 30$ km/sec, $\alpha = 1°$

No. of approximation	ψ	ψ_2	$\frac{\Delta P_v}{\Delta P_b} = \frac{\psi_2}{\psi_1}$	ΔP_b, kg/cm^2	R_2	r_2, km	r_0, m	τ	t_0, sec	t_b, sec	t_T, sec	l_T, km	v, km/sec	c, m/sec	α
1	25	21	5	0.012	53.6	24.7	460	43.6	1.69	74	10.7	11.4	1.06	372	20.5
2	46	42	10.5	0.0057	143	25.7	180	119	0.66	78.4	15.1	19.5	1.29	342	15.5
3	41	37	9.25	0.0065	120	25.5	213	99	0.785	77.7	14.4	17.4	1.21	348	16.75
4	42.25	38.25	9.55	0.00628	126	25.5	202	104	0.745	77.8	14.5	17.7	1.22	344	16.5
5	42	38	9.5	0.00632	125	25.5	204	103	0.752	77.8	14.5	17.7	1.22	344	16.5

the time of motion and the velocity of the cosmic body on the final segment of the trajectory (Table 2).

From the known pressure at the front of the ballistic wave at point P (Fig. 1), according to equation (3), the main parameters of the wave throughout space are determined uniquely, including the energy of the ballistic wave (Table 3).

Table 3

Parameters of the ballistic wave of the Tunguska cosmic body of 1908 at a distance of 25 km from the epicenter (at point P) for different flight altitudes

h, km	ΔP_v, kg/cm^2	$\Delta P_b = \frac{\Delta P_v}{10}$, kg/cm^2	$\bar{P}_1$, kg/cm^2	R_*	τ	r_2, m	r_0, m	$E_0 = r_0^2 \bar{P}_1$, erg/cm	$E_b = E_0 L$, erg	$t_0 = r_0 \sqrt{\frac{\bar{\rho}_1}{\bar{P}_1}}$, sec	$t_b = t_0 \tau$, sec
8	0.06	0.006	0.630	156	129	24700	159	$1.6 \cdot 10^{14}$	$3.9 \cdot 10^{20}$	0.578	74.7
10	0.06	0.006	0.563	134	111	25500	190	$2.0 \cdot 10^{14}$	$5.0 \cdot 10^{20}$	0.699	77.8

The average velocity of the Tunguska cosmic body on the final segment of the trajectory, about 18 km long, is 1.2 ± 0.4 km/sec. At such a low velocity, an explosion of the cosmic body due to kinetic energy is in principle impossible, since the kinetic energy at such a velocity is insufficient even for ordinary evaporation of this body.

It is obvious that the specific parameters of the ballistic wave impose quite definite restrictions on the size d_e and velocity v of the cosmic body ([3])

$$r_0 = \sqrt{\frac{c_x \gamma}{2} M d_e}.$$

According to this formula, at velocity $v = 1.2$ km/sec and $r_0 = 190$ m (Table 3), the effective diameter of a spherical body is $d_e = 65 \pm 15$ m (the actual diameter of the body may be smaller). Then the concentration of the energy released in the Tunguska explosion is $\sim 10^{12}$ erg/cm^3, which exceeds by 2 orders of magnitude the energy concentration of ordinary explosives.

From all that has been said, one may conclude that the Tunguska cosmic body exploded due to the internal energy of the body itself, with a large concentration of energy in a small volume, which cannot be provided by a chemical explosion of ordinary explosives.

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Volga–Ural Branch
of the All-Union Scientific Research Institute
of Geophysical Prospecting Methods

A. F. Ioffe Physico-Technical Institute
Academy of Sciences of the USSR

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