Quasi Three-dimensional Modeling of Tunguska Comet Impact (1908)

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The mechanism of Tunguska blast is determined as quick destruction of four main fragments of the comet in dense atmosphere. The structure of comet is determined, its substance and final size of each fragment. Detailed explanation of thermal damages due to explosion is described. More accurate coordinates of regions are obtained on the area of Tunguska site, where the most heavy sediments or fragments are possible to discover. Quasi three-dimensional modeling of the impact was produced with the help of PIC-method. It was shown that Tunguska-size comets are able to penetrate considerable deep into dense atmosphere due to decrease of drag effect. This decrease is explained by forward-directed jet from cavern of ice body, which located at the region of stagnation point. There is additional information for emergency organizations for training of people against comets and asteroids danger, its mechanical, thermal and electromagnetic influence.

Nomenclature

C_D	=	drag coefficient
α	=	initial trajectory inclination angle
V	=	velocity of entrance
C_H	=	heat transfer coefficient
Q	=	heat of ablation

I. Introduction

THIS investigation of Tunguska comet impact was produced during last 20 years. There is not necessity to describe history of all Tunguska investigations again, because many authors made it many times. The purpose of this paper is to give new vision of the problem and to initiate research process with new level of understanding. As a rule, the author of this paper describe below only aspects, which seems to be important for new vision of the problem. If necessary, the most interesting references concerning Tunguska investigations may be found in the book by Vasilijev[1].

II. Analysis of tree fall and burn

Attentive analysis was carried out by the author on the base of tree fall catalogue processing.[2] There is thin structure like “horseshoe” in southern area of tree fall (Fig. 1). This structure was interpreted by the author as influence of ballistic shock wave cone (gas dynamic

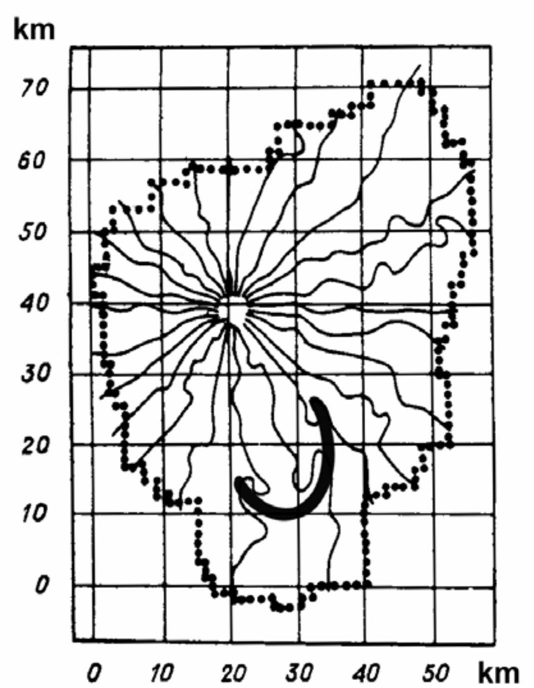

Figure 1. Thin structure like "horseshoe" in southern area of tree fall.

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caustic influence). The axis azimuth of "horseshoe" is in good correspondence to Astapovich's latest trajectory, which is directed from south-south-east to north-north-west.[3]

It is well-known that branches of trees were heated and burnt at the region of the Tunguska blast.[4] The author carried out special experimental investigation for determination of thermal properties of tree's rind and blast heat impulse. Rinds of pine and larch were investigated during heating by electrical heater. Experimental equipment consisted of electrical heater, thermocouples as gauges, analogue-digital converter and personal computer as recorder. Obtained thermal properties were used for calculations of temperature distribution in cross section of branches. Heat impulse was determined during analysis with 2-D finite element method. Also, influence of heat impulse and thermal damages of vegetation's sediments were investigated directly in the site of Tunguska catastrophe. The author made more than ten prospect-holes in peat-bogs during expedition of 1988. It became possible to compare view of real thermal influence in the site and results of calculated heat impulse.

Area of burn[4] was closely inspected too. Clear picture of heat influence was obtained in accordance to value of heat impulse and clustering procedure (Fig. 3). Three considerable blasts here are visible (central **A**, eastern **B** and western **C**). Fourth blast **D** is visible on some distance to north-west. Also three "horseshoe-like" burn structures **E** are visible on some distance to south. This picture is interpreted as blasts of four fragments and heat radiation influence by ballistic shock wave's surface (heat caustic influence).

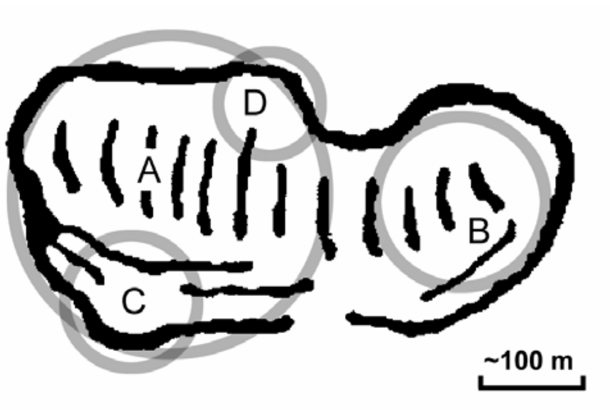

Figure 2. The Tunguska space body at flight.

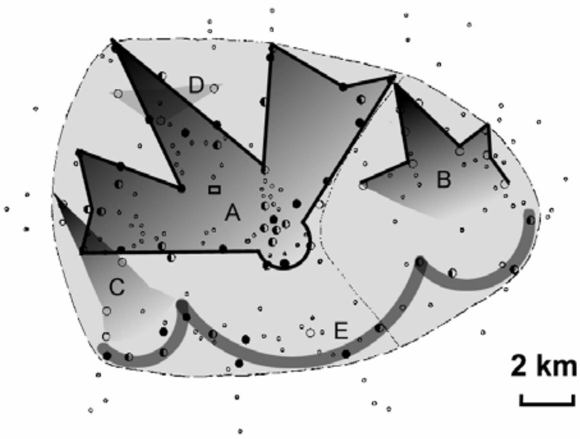

Figure 3. Explanation of heat influence field.

It is necessary to mention the picture of the Tunguska space body at flight, which was drawn by eyewitness Naumenko[5] from the town Kezhma (Fig. 2). There is good correspondence between this picture and thin structure of burn (Fig. 3). Scale is added by the author of paper.

III. Numerical modeling

Mentioned above results of analysis gave accurate (a priori) information for quasi 3-D modeling. The modeling dealt with estimation of unsteady temperature distribution in the Tunguska space body before entering into atmosphere, estimation of mechanical properties of the body in accordance to its temperature, solution of equations of motion (three coordinates), calculations of pressure, heat and mass transfer at the region of stagnation point (for all body and then for all its fragments), strength and stress analysis for all body and then for all its fragments, deformation of all fragments, expansion of hot gas volumes in case of its known geometry, shock wave formation and heat radiation influence on forest and branches of trees, formation and raising of hot cloud, variation of local magnetic field. This model was called by the author of paper as "model of four steam-boilers".

In accordance to Astapovich, initial trajectory inclination angle was taken between α=5º-7º. Velocity of entrance into atmosphere was taken as V=11.2 km/s. Heat transfer coefficient C_H was variable between 0.02 and 0.1. Heat of ablation the author consider $Q=2.5\cdot10^6$ J/kg. Calculated length of trajectory as function of altitude is shown in Fig. 4.

Expansion of hot gas volumes was calculated with the help of particle-in-cell method[6] (PIC). The author made special computer program based on PIC algorithm for calculations of gas expansion in horizontal plane. PIC-method is convenient for solution of this task because borders of hot gas volumes in the case of Tunguska blast are considerably curved. Also these calculations are more determined due to well-known geometrical form of each initial gas volume. Pressure, velocity and temperature distributions were estimated during calculations. Calculation process consisted of cells grid generation, initial positioning of particles, initial and boundary conditions set, solution of gasdynamic equations with Eulerien and Lagrangian procedures with time steps. Typical grid of cells was (50 x 50). Quantity of air particles was 4 per cell and quantity of comet's substance particles - 300 per cell. The view of initial distribution of all particles is visible in Fig. 5. Model form of gas volume was stated approximately in accordance to form of blasts **A** and **B** (Fig. 3). The sample of pressure calculation is shown in Fig. 6. Influence of ballistic shock wave on southern direction was taken into consideration in accordance to analogy of cylindrical explosion[7].

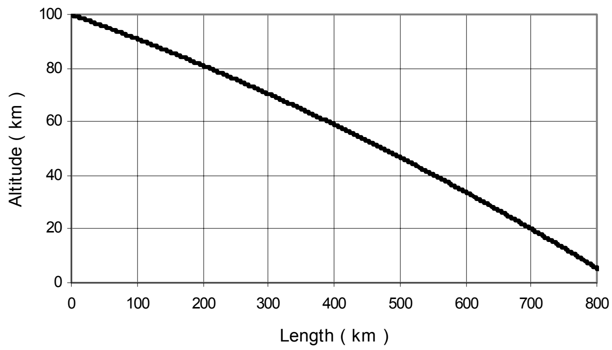

Figure 4. Length of trajectory as function of altitude.

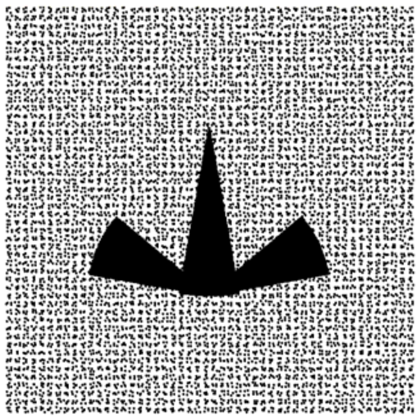

Figure 5. The view of initial particles distribution.

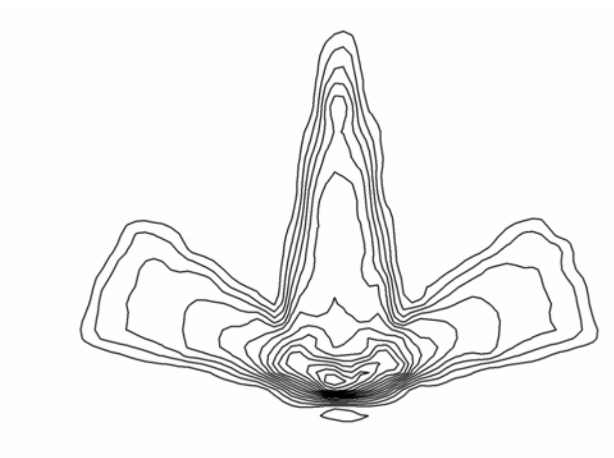

Figure 6. The sample of pressure calculation.

IV. Results

Results are described below as a number of brief positions.

Total energy of Tunguska impact, which determined tree fall in the form of "butterfly" (Fig.1), is in good correspondence to $5{,}6 \cdot 10^{16}$ J. Final total mass of all Tunguska fragments was 10 million tons (at the end of trajectory in atmosphere).

The Tunguska space body was typical nucleus of comet with the same size relations between its fragments. Size relations between diameters of the Tunguska four fragments A,B,C,D are included below in Table 1.

During modeling was noticed good correspondence to typical density of comet substance with average value ~0.6 g/cm^3. The most of internal substance of the Tunguska comet is determined as water ice.

Substance of all Tunguska fragments was considerably uniform and all fragments were scattered on equal lateral distance ~7 km.

Approximate coordinates of the most probable regions, where small heavy fragments may be discovered, are presented in Table 2. These regions are determined as initial points of blasts. Here are relative coordinates of these points, where main houses of Kulik's expedition's base are marked too (near the Stoikovich Mountain).

Final effective velocity of fragments before blasts is determined as ~2.2 km/s.

Expansion of final hot gas volumes took place mainly in horizontal plane on altitude of ~4-6 kilometers.

Northern wing of "butterfly" was produced mainly by four final horizontal-directed blasts, but southern wing was produced mainly by ballistic and ablation shock wave. The influence of ballistic shock wave was increased due to concave form of trajectory.

Initial form of gas volume, which was produced by fragment **A** or **B**, contained considerable cavern near stagnation point.

Sample of parameters for the blast of fragment **A** is presented in Table 3.

Σ-like borders of blasts **A** and **B** are well modeled from position of hot gas viscosity influence. There is method of comet gas viscosity estimation.

Heat impulse of the blast **B** is determined as 13 J/cm^2. Heat impulse of every "horseshoe-like" burn structure **E** is determined as 30 J/cm^2.

There is effect of decrease of aerodynamic resistance coefficient (C_D - drag coefficient) due to directed jet from cavern. This cavern is formed due to most intensive heat and mass transfer processes at the region of stagnation point. The same effect is described in the book by Sedov.[8] In case of jet from cavern at the region of stagnation point, drag effect is reduced. The effect was tested during calculations by the author of this paper. For sphere the author has taken drag coefficient approximately as ~0.5 instead of 1.0 and for cylinder ~0.85 instead of 1.7. This effect promotes more deep penetration of comet into dense atmosphere.

Table 1

Fragment	D, m	Relation
A	295	$D_A = 1$
B	150	$D_A / D_B = 1.9$
C	120	$D_A / D_C = 2.4$
D	95	$D_A / D_D = 3.1$

Table 2

	X	Y
Base	0.497	0.554
A	0.654	0.437
B	1.069	0.490
C	0.321	0.272
D	0.374	0.751

Table 3

Energy of blast, J	$2.4\cdot10^{16}$
Area of flare, m^2	$5.8\cdot10^{7}$
Thickness of flare, m	90
Initial temperature, K	1700
Initial pressure, Pa	$1.3\cdot10^{6}$
Heat impulse, J/cm^2	30

Upper limit of compression strength of Tunguska internal comet ice is determined as $1.3\cdot10^6$ Pa. The Tunguska trajectory in atmosphere is in good correspondence to Astapovich's latest trajectory.[3] It is strongly confirmed that azimuth angle and inclination angle of fragments trajectories were considerably variable during motion in atmosphere. Near final point of trajectory the angle of trajectory's inclination and vertical component of velocity were considerably increased.

Results of modeling are in good correspondence to theoretical model by Tsinbal and Shnitke.[9,10] There is the difference too. There is not necessity on considerable additional chemical energy for blasts. Also the decreasing of drag effect is taken into consideration.

It is not excluded that the effect of magnetic cumulation[11] may produce considerably high magnetic fluctuations in case of giant meteoroids.

V. Conclusion

The nature of Tunguska event, internal structure of this concrete comet and its substance became clear. It was shown that Tunguska-size comets are able to penetrate considerable deep into dense atmosphere of Earth.

New aspects of comet danger are discovered. For example, there is formation of "horseshoe-like" burns. The cavern was noticed as factor of danger. Also, considerably increasing lateral distance between fragments of comet during motion in atmosphere means additional danger etc. Some methods of defense against comets and asteroids are suggested which based on results of the study.

More accurate data concerning the Tunguska event will be obtained on the base of full three-dimensional modeling.

Acknowledgments

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3-D calculation scheme (final part of trajectory)