Entry of the Tunguska Cosmic Body into the Atmosphere: Final Decision

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[Abstract] When meteorites move in the atmosphere, the relative role of evaporation is characterized by a mass loss parameter. In this work, it is shown that the properties of solutions for the main system of equations of meteor physics, along with the results of the independent numerical experiment, provide the conclusion that the well-known Tunguska impact event that happened on June 30, 1908 was a giant micrometeorite, i.e., an ordinary phenomenon that differed from daily micrometeorites only in the scale expressed by the huge mass of the meteorite.

Nomenclature

H^*	=	effective destruction enthalpy
h	=	height
M	=	mass of a body
S	=	area of middle section
V	=	velocity
α	=	ballistic parameter
β	=	mass loss parameter

I. Introduction

The solution of equations of meteor physics

$$m = \exp\left[-\beta\left(1 - v^2\right)\right], \quad y = \ln\alpha + \beta - \ln\frac{\Delta}{2}, \quad \Delta = \overline{E}i(\beta) - \overline{E}i(\beta v^2), \quad \overline{E}i(x) = \int_{-\infty}^{x}\frac{e^t dt}{t} \tag{1}$$

shows that the trajectory depends on the following two dimensionless parameters (Stulov *et al.*, 1995):

$$\alpha = \frac{1}{2} c_{в} \frac{\rho_0 h_0 S_e}{M_e \sin\gamma}, \quad \beta = \frac{c_h V_e^2}{2 c_d H^*}. \tag{2}$$

Here, the trajectory angle γ, drag coefficient c_d, heat-exchange coefficient c_h, and effective destruction enthalpy H^* are constant values. Formulas (2) include the body velocity V_e, body mass M_e, and the midlle section area S_e at the entry into the atmosphere, as well as the homogeneous atmosphere height h_0 and the gas density ρ_0 at sea level. The parameter α characterizes the drag intensity because it is equal to the ratio of the mass of the atmospheric column with the cross section S_e along the trajectory to the body mass. The parameter β is proportional to the ratio of the fraction of the kinetic energy of the body's unit mass that is supplied to the body in the form of heat to the effective evaporation enthalpy.

The relative roles of the disintegration, deceleration, and evaporation can be characterized by the parameter β. Small β values correspond to the entry of quite heat-resistant objects with relatively low velocities. If the strength of the body is low, it is disintegrated into numerous fragments, whereas mass loss owing to the blowing of a liquid film, as well as the evaporation of the body material on its face, is relatively small. As a result, this case corresponds to the fall of numerous fragments on the surface of a planet, which is accompanied by the formation of meteorite and crater fields.

At moderate β values, the roles of the disintegration and evaporation in the process of the interaction of the meteoroid with the atmosphere are comparable. In dependence on the morphological properties of the body, disintegration can occur either into fragments at one or several stages or gradually through successive separation of small fragments from the parent body. Small fragments are decelerated more rapidly and lag behind large fragments. Owing to this behavior, the role of evaporation on small fragments rapidly becomes secondary.

Finally, large β values correspond to the predominant gasification of the body either as a whole or in the form of the fragment cloud. In this case, the evaporation (and disintegration) occurs at the relatively early stage of entry into the atmosphere so that the deceleration of the meteoroid in the solid phase is negligible. The asymptotic solution (Stulov, 1994) of equations for the trajectory at $\beta >> 1$ shows that evaporation is almost completed at the velocity equal to the entry velocity.

II. Real Events

Let us consider examples of well-known real falls corresponding to these three ranges of the parameter β: the Sikhote-Alin meteorite fall (SAM, February 12, 1947; (Fesenkov, 1951)); the Benesov bolide, detected by the Czech part of the European Fireball Network (B, May 7, 1991; (Spurny, 1994)); and the Tunguska cosmic body (TCB, June 30, 1908; (Korobeinikov *et al.*, 1991)), which is studied in detail but still initiates serious disagreements and discussions. The abbreviation used below for the name of an event, its date, and reference are given in the parentheses after the name of each event. The scientific literature devoted to each event includes many works, but only those works are given from which quite reliable, on my opinion, numerical data used below are taken.

Table 1. Mass loss parameter in real meteor phenomena

Event	V_e, km/s	H^*, 10^3 J/g	c_h		β	
			estimate	calculat.(2)	estimate	calculat.(2)
SAM	14.5 (3)	8 (6)	0.010	0.018	0.13	0.23
B	21.8 (4)	2 (2)	0.012 (4)	0.018	1.35	2.03
TCB	35 (5)	2 (1, 2)	0.100	0.090	30.63	27.57

List of references in the table:
1. Shuvalov and Artemieva, 2002
2. Stulov *et al.*, 1995
3. Fesenkov, 1951
4. Spurny, 1994
5. Korobeinikov *et al.*, 1991
6. Chyba *et al.*, 1993

The table presents the β values for each of the three events and the sources for some of the initial data. The calculated c_h and β data are obtained using the approximate method for calculating c_h that was described in detail in (Stulov *et al.*, 1995). As was mentioned above [below Eqs. (2)], the heat-exchange coefficient c_h is taken as a constant in the table. It was estimated using the parameters of the entry into the atmosphere and the characteristic altitude of the real event (disintegration, glowing, etc.). The calculated c_h values depend on the entry velocity V_e, characteristic initial body dimension R and ambient air density.

For all cases, $c_d = 1$ is taken. According to the table, the calculated β values are close to the respective estimated values; in any case, both calculated and estimated β values for all real events differ approximately by an order of a magnitude.

Thus, the parameter α characterizes the deceleration rate when passing through the atmosphere, whereas the parameter β characterizes the role of thermochemical destruction and mainly determines the basic consequences of the entry of a meteorite into the atmosphere. The mechanical disintegration occurs almost always. Therefore, the above consideration of the parameters α and β refers to both the original meteoroid and its fragments.

A considerable excess of the specific (per unit mass) kinetic energy carried to the atmosphere by the Tunguska object and its fraction supplied to the body in the form of heat over the energy necessary for the evaporation of a mass unit of its body caused rather unusual consequences of the Tunguska fall on June 30, 1908. These consequences are the complete absence of craters and fall and burn of taiga on a vast area whose characteristic size is approximately three orders of a magnitude larger than the probable geometric size of the Tunguska cosmic body. These features show that the action of the remnants of the Tunguska cosmic body on the ground is, most probable, that of a pure gasdynamic character.

III. Asymptotic Solution and Numerical Experiment

As was shown for the first time in (Stulov, 1994), the asymptotic solution of equations of meteor physics for large β values has the form

$$v = 1, \quad m = 1 - 2\alpha\beta e^{-y} \tag{3}$$

This means that a meteorite characterized by a large β parameter is rapidly evaporated without deceleration. After the complete evaporation, fast deceleration of the products in the mixture with ambient air must occur. This idea was developed in my more recent works (Stulov, 1997; Stulov, 1998a; Stulov, 1998b).

In the second half of the 1990s, researchers discussed a new colossal bolide phenomenon: the fall of the fragments of the Shoemaker-Levy 9 comet on Jupiter observed in summer 1994. It appeared that some nature observations of this phenomenon are explained by the proposed hypothesis of the behavior of bolides for large β values. American authors (see, e.g., Hammel et al., 1995) published photographs of a giant gas blowout outside Jupiter's atmosphere, which were obtained on the Hubble Space Telescope satellite after the entry of large fragments of the comet into the atmosphere. These were likely bunches of hot products from the evaporation of fragments in the mixture with the atmospheric gas that were blown out of the atmosphere by buoyancy forces.

The results of the numerical simulation (Shuvalov and Artemieva, 2002) of the entry of large bolides into the atmosphere of planets completely confirm the basic properties of asymptotic solution (3).

The motion of a spherical body 30 m in radius in the Earth's atmosphere perpendicularly to the ground was calculated by numerically solving equations of inviscid gas dynamics with the initial conditions V_e = 30 km/s at h = 30 km. The complete evaporation of the solid phase ends at the altitude of h = 11 km, and the "visible velocity of the meteor," i.e., the remnants of the meteoroid and surrounding evaporation products, is equal to 25 - 26 km/s. At the subsequent stage of the calculation, the air-vapor jet is decelerated to zero velocity at an altitude of 4 km and, after that, the hot gas volume ascends owing to buoyancy forces. The characteristic transverse radius of the jet at the deceleration time exceeds 2 km. According to this brief consideration, the basic properties of the asymptotic form of the trajectory of a bolide, which were obtained from equations of meteor physics (Stulov, 1994), were first demonstrated in calculations reported in (Shuvalov and Artemieva, 2002). These properties imply the almost complete ablation of the meteoroid under the conditions of slow deceleration. These properties are illustrated in Fig. 1, where the relative mass $m = M/M_e$ and velocity V of the body are shown as functions of the flight altitude H. The solid lines correspond to numerical solution (Shuvalov and Artemieva, 2002) and the dashed lines represent solution (3), constructed with the parameters of the bolide for the meteoroid density ρ_m = 1.5 g/cm^3. The dash-dotted line in Fig. 1b shows the velocity of the gas volume, which is not determined in the asymptotic solution.

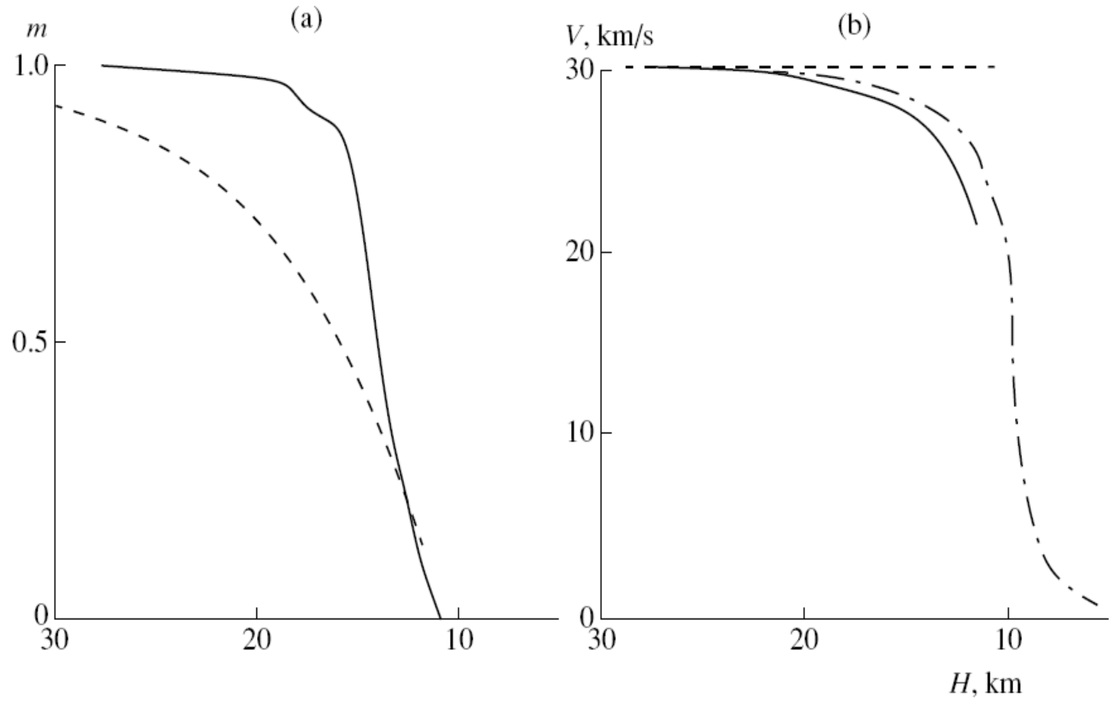

Figure 1. (a) The relative mass and (b) velocity of the solid meteoroid vs. the flight altitude: the solid lines are the results of numerical solution (Shuvalov and Artemieva, 2002) and dashed lines are asymptotic solution (3) at $\alpha = 0.077$ ($\rho_m = 1.5$ g/cm^3) and $\beta = 30$.

It is worth noting that this calculation does not reproduce all important details of the entry of the Tunguska cosmic body into the Earth's atmosphere. However, it can be assumed that change in the initial conditions, e.g., to $V_e = 35$ km/s and $R_e = 38$ m (Korobeinikov *et al*., 1991), will provide the reproduction of the fall of the air-vapor jet on the taiga and its spreading accompanied by burn and fall of the forest.

IV. Conclusion

Thus, a certain dependence of the character of the bolide on the mass loss parameter β is demonstrated in this work. This dependence allows a more certain interpretation of large falls, in particular, by excluding fantastic or half-fantastic scenarios.

For large β values, the evaporation of the fragments of the destroyed meteorite is the predominant process. This evaporation occurs without fast deceleration. Therefore, the interaction of the bolide with the planet surface can be purely gasdynamic.

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