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Deceleration rate of a fireball as a tool to predict consequences of the impact

Maria Gritsevich[1,2,3], Daria Kuznetsova[2], Vladimir Stulov[2], and Leonid Turchak[3]

[1] **Finnish Geodetic Institute, Geodeetinrinne 2, P. O. Box 15, FIN-02431 Masala, Finland**

[2] **Institute of Mechanics and Faculty of Mechanics and Mathematics, Lomonosov Moscow State University, Michurinsky Pr. 1, Moscow, 119192, Russia**
gritsevich@list.ru, morven9@yandex.ru

[3] **Dorodnitsyn Computing Center, Russian Academy of Science, Vavilova Ul. 40, Moscow, 119333, Russia**
turchak@ccas.ru

The correct interpretation of fireball observations is a very important task, since it could promptly confirm a fresh meteorite fall, and, furthermore, provide a link to its parent body. Based on the analysis of the fireball aerodynamic equations, we describe the possible results that might accompany collisions of cosmic bodies with the Earth's atmosphere and surface. After integrating, these equations characterize the body's trajectory in the atmosphere very well, while the exact derived dependency of the body's velocity on the height of the fireball can be further compared to the observations. The solution depends on two key dimensionless parameters defining the meteoroid drag and mass loss rate in the atmosphere.

1 Introduction

The study attempts to classify meteor events and predict their consequences with respect to values of the basic dimensionless parameters derived from the aerodynamic equations. Two key parameters have the following physical meaning:

1. the ballistic coefficient α characterizes the aerobraking efficiency. It is proportional to the ratio between the mass of the atmospheric column along the trajectory with cross section S_e to the meteoroid initial mass;

2. the mass loss parameter β is proportional to the ratio of the fraction of the kinetic energy of the body's unit mass arriving at the body in the form of heat to the effective destruction enthalpy.

For each given fireball case, these parameters can be found by comparing the theoretical curve of equation (8) with the actual rate of body deceleration in the atmosphere as described in the following section.

2 Aerodynamic model

The physical problem of the meteor body deceleration in the atmosphere has been considered in a number of papers and monographs (see, e.g., Stulov et al, 1995). The classical dynamic third-order system has been constructed, where the body mass $M(t)$, its height above the planetary surface $h(t)$, and its velocity $V(t)$ are the phase variables. The equations of motion projected onto the tangent and to the normal to the trajectory appear as

$$M\frac{\mathrm{d}V}{\mathrm{d}t} = -D + P\sin\gamma; \tag{1}$$

$$MV\frac{\mathrm{d}\gamma}{\mathrm{d}t} = P\cos\gamma - \frac{MV^2}{R}\cos\gamma - L; \tag{2}$$

$$\frac{\mathrm{d}h}{\mathrm{d}t} = -V\sin\gamma, \tag{3}$$

with $D = c_D\rho_\mathrm{a}V^2S/2$ the drag force, $L = c_L\rho_\mathrm{a}V^2S/2$ the lifting force, and $P = Mg$ the body weight. Here, M and V are the body's mass and velocity, respectively; t is the time; h is the height above the planetary surface; γ is the local angle between the trajectory and the horizon; S is the area of the cross section of the body; ρ_a is the atmospheric density, g is the acceleration due to gravity; R is the planetary radius; and c_D and c_L are the drag and lift coefficient, respectively.

Equations (1)–(3) are complemented by the equation for the variable mass of the body:

$$H^*\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{1}{2}c_H\rho_\mathrm{a}V^3S \tag{4}$$

where H^* is the effective enthalpy of destruction and c_H is the coefficient of heat exchange. It is assumed that the entire heat flux from the ambient gas is spent to the evaporation of the surface body material.

Using equation (3), it is possible to introduce a new variable h and pass to convenient dimensionless quantities $M = M_\mathrm{e}m$, $V = V_\mathrm{e}\nu$, $h = h_0y$, $\rho_\mathrm{a} = \rho_0\rho$, and $S = S_\mathrm{e}s$, where h_0 is the height of the homogeneous atmosphere, ρ_0 is the atmospheric density near the planetary surface, and the subscript "e" refers to the parameters at atmospheric entry. Since the velocities in the problem under consideration are sufficiently high (in the range from 11 to 72 km/s), the body's weight in equation (1) is conventionally neglected (Gritsevich, 2010). Variations in slope γ are not significant, and usually they are not taken into account. With allowance for the above considerations, the equations for calculating the trajectory eventually acquire the following, more simple form:

$$m\frac{\mathrm{d}v}{\mathrm{d}y} = \frac{1}{2}c_D\frac{\rho_0 h_0 S_\mathrm{e}}{M_\mathrm{e}}\,\frac{\rho \nu s}{\sin\gamma}; \tag{5}$$

$$\frac{\mathrm{d}m}{\mathrm{d}y} = \frac{1}{2}c_H\frac{\rho_0 h_0 S_\mathrm{e}}{M_\mathrm{e}}\,\frac{V_\mathrm{e}^2}{H^*}\,\frac{\rho \nu^2 s}{\sin\gamma}. \tag{6}$$

To find the analytical solution of equations (5)–(6), we assume that the atmosphere is isothermal: $\rho = e^{-y}$. Following Levin (1956) we also assume that the cross section and the mass of the body are connected by the relationship $s = m^\mu$, where the constant parameter μ characterizes the possible role of rotation during the flight. With these assumptions, the solution of equations (5)–(6) with the initial conditions $y = \infty$, $\nu = 1$, and $m = 1$ has the form

$$m = e^{-\frac{\beta}{1-\mu}(1-v^2)}; \tag{7}$$

$$y = \ln\alpha + \beta - \ln\frac{\Delta}{2}; \tag{8}$$

$$\alpha = \frac{1}{2}c_D\frac{\rho_0 h_0 S_\mathrm{e}}{M_\mathrm{e}\sin\gamma}; \tag{9}$$

$$\beta = (1-\mu)\frac{c_H V_\mathrm{e}^2}{2c_D H^*}, \tag{10}$$

where α is the ballistic coefficient, β is the mass loss parameter, and Δ is short for $\mathrm{Ei}(\beta) - \mathrm{Ei}(\beta\nu^2)$, with $\mathrm{Ei}(x)$ the exponential integral[1].

In the remainder of this paper, we use the analytical solution (8) as the general theoretic height-velocity relation.

The values of the parameters α and β providing the best fit of the observed physical process can be found by the method proposed by Gritsevich (2009). The sum of the squared deviations of the actually observed altitudes h_i and velocities V_i of motion at certain points $i = 1, \ldots, n$ of the desired curve described by equation (8) from the corresponding values e^{-y} calculated using equation (8) is used as the fitting criterion. Then the desired parameters are unambiguously determined by the following formulae:

$$\alpha = \frac{\sum\limits_{i=1}^{n} e^{-\beta-y_i}\Delta_i}{2\sum\limits_{i=1}^{n} e^{-2y_i}}; \tag{11}$$

$$\sum_{j=1}^{n}\left\{\left[\Delta_j\sum_{i=1}^{n}e^{-2y_i} - \left(\sum_{i=1}^{n}\Delta_i e^{-y_i}\right)e^{-y_j}\right]\left(\Delta_j - \frac{\mathrm{d}\Delta_j}{\mathrm{d}\beta}\right)\right\} = 0; \tag{12}$$

$$\frac{\sum\limits_{i=1}^{n}e^{-2y_i}\sum\limits_{i=1}^{n}\left[\left(\frac{\mathrm{d}\Delta_i}{\mathrm{d}\beta}-\Delta_i\right)^2+\left(\Delta_i-2\alpha e^{\beta-y_i}\right)\right]\left(\frac{\mathrm{d}^2\Delta_i}{\mathrm{d}\beta^2}-2\frac{\mathrm{d}\Delta_i}{\mathrm{d}\beta}+\Delta_i\right)}{\left[\sum\limits_{i=1}^{n}e^{-y_i}\left(\Delta_i-\frac{\mathrm{d}\Delta_i}{\mathrm{d}\beta}\right)\right]^2} > 1. \tag{13}$$

Here, $\nu_i = V_i/V_e$, $y_i = h_i/h_0$, and $\Delta_i = \mathrm{Ei}(\beta) - \mathrm{Ei}(\beta\nu_i^2)$.

[1] $\mathrm{Ei}(x) = \int_{-\infty}^{x} u^{-1}\exp(u)\mathrm{d}u$.

The obtained parameters are used to calculate the mass of a meteor body, the effective enthalpy of evaporation, and other important parameters. The complete algorithm of deriving luminous efficiency and shape change coefficients is described in details by Gritsevich and Koschny (2011). The initial mass M_e and mass in any other point along the trajectory can be estimated using the found values of the ballistic coefficient α and mass loss parameter β in the following way (see, e.g., Gritsevich, 2008a; 2008b):

$$M_\mathrm{e} = \left(\frac{c_D A_\mathrm{e}}{2}\,\frac{\rho_0 h_0}{\alpha\sin\gamma}\right)^3\rho_\mathrm{b}^{-2} \tag{14}$$

$$\frac{h}{h_0} = \ln(2\alpha) + \beta - \ln\left[\mathrm{Ei}(\beta) - \mathrm{Ei}\left(\beta + (1-\mu)\ln\frac{M}{M_e}\right)\right], \tag{15}$$

where ρ_b is the bulk density of the meteoroid body, and A_e its pre-entry shape factor[2].

3 Basic conclusions and results

Below, we propose several examples of collisions of cosmic bodies with the Earth and their consequences. Figures 1 and 2 further illustrate them. These examples are supplemented by a brief analysis of the actual events (Gritsevich et al., 2012).

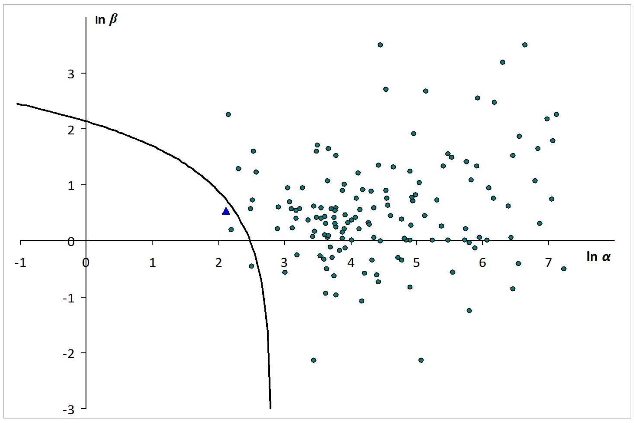

Figure 1 – Distribution of parameters α and β for the fireballs registered by the Meteorite Observation and Recovery Project in Canada (Halliday et al., 1996). The filled triangle corresponds to the unique meteorite found on the ground in the context of the project (Innisfree). The curve shows our analytically derived margin between the region with expected meteorites on the ground and fully ablated fireballs.

1. The range $\alpha \ll 1$, $\beta \ll 1$: The impact of a unified massive body with the Earth's surface results in the formation of a vast crater. The large body's mass minimizes or entirely excludes the effect of the atmosphere. Almost certainly, the atmosphere is penetrated by a cosmic body without its fracture. An illustrative example is the Barringer Crater in the state of Arizona, United States.

[2] $A_\mathrm{e} = S_\mathrm{e}\rho_\mathrm{b}^{2/3}/M_\mathrm{e}^{2/3}$.

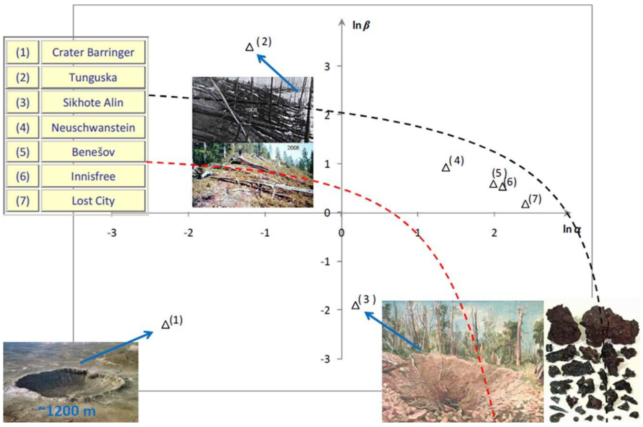

Figure 2 – The leftmost curve shows the margin for the region with crater formation; the rightmost curve the margin for meteorite survivors.

2. The range $\alpha < 1$, $\beta < 1$: fracture of the meteor body in the atmosphere and deposition of a fragments cloud onto the Earth's surface take place with the formation of a crater strew field with corresponding meteorite fragments. Modern mathematical models describing the motion of the fragments cloud in the atmosphere allow us to predict basic geographic and other features of these fields. The ablation effect on the motion of the fragments is of minor importance. An illustrative example is the Sikhote-Alin meteorite shower (Primorsky Krai, Russia, 1947).

3. The range $\alpha \approx 1$, $\beta \approx 1$. These conditions are close to those of the preceding section. However, they are characterized by a more significant role of ablation. As obvious examples, we can indicate reliably documented fireballs for which part of the luminous segment of the atmospheric trajectory were observed, meteorite fragments being also found in a number of cases. Among them, there are the famous bolides Neuschwanstein (Bavaria, Germany, 2002), Innisfree (Alberta, Canada, 1977) and Lost City (Oklahoma, USA, 1970). They are relatively small meteoroids, thus the total mass of meteorites collected on the Earth's surface is in the order of 10 kg (see, e.g., Gritsevich, 2008a). The absence of craters is explained by the same reason. The characteristic feature of the collected meteorite fragments is the presence of ablation traces on their outside surface covered by fusion crust.

4. The range $\alpha < 1$, $\beta \gg 1$: fracture and complete evaporation of a meteoroid in the atmosphere take place at the low velocity loss. The characteristic consequence of these events is the fall of a high-speed air-vapor jet onto the Earth's surface. Descending in the atmosphere, the gas volume expands (Turchak, 1980). Then, the gas cloud arrives at the Earth's surface, which is accompanied by the formation of a high-pressure region, and flows around its relief. As a result, the characteristic size of the impact region exceeds the characteristic size of the original meteoroid by several orders of magnitude. The Tunguska Event (Krasnoyarski Krai, Russia, 1908) serves as a real example of an event of this type.

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