Effects of bolide parameters on the motion and destruction in the Earth’s atmosphere

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Abstract. The present work describes numerical studies of movement and destruction of four meteoroids in the Earth's atmosphere: the Sikhote-Alin (1947), the Beneshov (1991), the Kunya-Urgench (1998) and the Chelyabinsk (2013) ones, which differ considerably in their dimensions, material properties, and trajectory parameters. The meteoroid mass loss due to radiation and thermal effects, and fragmentation of bodies during the motion along their trajectories is considered. These meteorites were chosen for the verification of newly developed models and to illustrate the impact of their parameters on the processes of movement and destruction.

Keywords: meteoroid, motion, destruction, heat transfer, fragmentation

1. Introduction

The work is devoted to mathematical modeling of the dynamics and destruction of meteoroids in the Earth's atmosphere. The destruction of a meteor in the Earth's atmosphere is influenced by many factors. In most parts of the trajectory, there is an intensive loss of mass under the action of radiation and convective heat transfer. In addition, a single or multiple fragmentation into smaller bodies may occur. The processes of their interaction with the atmosphere are affected by the speed and the angle of entry into the atmosphere, as well as thermophysical and strength characteristics of the material.

The Earth's atmosphere completely "destroys" a relatively small body and is able to significantly impact large meteorites. When moving in the atmosphere meteoroids cause the phenomenon of a meteor or "shooting stars". Especially bright meteors are bolides, which can be pretty large. These will be considered in this work.

Each meteor body is quite individual. In this regard, the study of motion and destruction of each individual meteoroid is a separate task.

This paper analyses the movement and destruction in the atmosphere of four specific meteoroids: the Chelyabinsk (2013), the Sikhote-Alin (1947), the Beneshov (1991), and the Kunya-Urgench (1998) ones, under the action of heat and power loads. The subjects of the study vary in their size, material and trajectory parameters.

The first two bodies are relatively large, their size is of the order of several meters in diameter, the size of the other two is about 1 m. The parameters of these bodies are presented in Table.1.

These meteorites were selected for the verification of the developed models not only as objects with a sufficient amount of data available about them, but also as strongly distinguished objects. Observations data were employed for a better understanding of the phenomena occurring on the path of the bodies.
Table 1. The parameters of meteoroids

| Name of the meteorite                  | Entry speed, km/s | Entrance angle, degrees | Weight of the meteorite, t | Composition of the material; density, g/cm³ |
|----------------------------------------|-------------------|-------------------------|-----------------------------|--------------------------------------------|
| Chelyabinsk (Chebarkul) (2013)         | 19.2              | 18                      | 13000                       | stone chondrite; 3.3                        |
| Sikhote-Alin (1947, Primorsky Krai)    | 15                | 41                      | 500                         | iron; 7.8                                  |
| Beneshov (1991, Czech Republic)        | 21                | 45                      | 3.5                         | stone; 3.7                                 |
| Kunya-Urgench (1998, Turkmenistan)     | 13                | 30                      | 3                           | stone chondrite; 3.3                        |

2. Basic equations

A numerical study of the problem is based on the equations of the physical theory of meteors in the form of [1] considering the motion in an exponential atmosphere \( \rho = \rho_0 \exp(-z/h) \) \( (z \) is the altitude position of the meteoroid over the Earth's surface, \( \rho_0 \) is the atmospheric density at \( z = 0 \), \( h \) is the characteristic height scale):

\[
M \frac{dV}{dt} = Mg \sin \theta - C_D S_{mid} \frac{\rho V^2}{2},
\]

\[
V \frac{d\theta}{dt} = g \cos \theta - \frac{V^2 \cos \theta}{R_e + z},
\]

\[
H_{eff} \frac{dM}{dt} = -C_H S_{mid} \frac{\rho V^3}{2},
\]

\[
\frac{dz}{dt} = -V \sin \theta,
\]

where \( V, M, \theta \) are the velocity of the body, its mass and the inclination angle of the trajectory of the fall to the horizon; \( R_e \) is the radius of the Earth; \( C_D, C_H, H_{eff} \) are coefficients of resistance, heat transfer to the body surface and the effective enthalpy of vaporization of the meteoroid; \( S_{mid} \) – sectional area of the body.

Tremendous speed (~10-30 km/s) of meteoroids causes them to experience pressures and temperatures of the order of tens to thousands of atmospheres and thousands of degrees. Under these conditions there are two heat transfer mechanisms from the gas to the body surface: convective heat transfer and radiation heat transfer.

To determine the convective heat flux at the critical point of the surface of a spherical meteorite, the following formula is used [2]:
$$q_{c0} \approx 3.3 \cdot 10^{-5} \left( \frac{\rho_{\infty}}{R} \right)^{1/2} V_{\infty}^{3/2}, \text{ W/m}^2$$

Here $R$ is in m, $\rho_{\infty}$ in kg/m$^3$, $V_{\infty}$ in m/s. The index "$\infty$" corresponds to the parameters of the incoming flow.

For the coefficient of radiant heat transfer at the critical point the ReVelle formula is applied, the parameters of which are presented in [1]:

$$C_{hr} = f \cdot e^{\alpha_0} \rho^{A_1 + A_2 V^{n-1}} R^{A_3 + A_4 V + A_5 V^2} V^{A_6 + A_7 V + A_8 V^2 - 3}$$

Accordingly, the heat flux at the critical point will be presented as $q_{c0} = 0.5 \rho_{\infty} V_{\infty}^3 C_{hr}$.

The distribution of heat transfer along a spherical surface for convective heat transfer is approximated by the formula [3]:

$$q_c = q_{c0} (0.55 + 0.45 \cos 2\beta),$$

where $\beta$ is the angle of the meridian cross-section counted from the direction to the critical point; and the radiation flux [4] $-q_r = q_{c0} \cos^n \beta$, $n = 1/((0.051 V - 0.43) + 1.811$.

The total heat transfer to the body surface is defined as the sum of convective and radiative heat flux.

When a large heat flux to the body surface is evaporating the surface of the body, it can lead to a significant weakening of the convective heat flux and even to full shielding of its effect [5]. Radiant heat flux can also be shielded by the injected gas, however, complete a shielding does not occur even with an intense injection [6]. The main quantitative determinant of the ratio of screened radiant energy is the spectral composition of the radiation, not the intensity of the injection, as in the case of evaporation under the action of convective heat transfer. Therefore, according to [7], the radiant heat transfer coefficient at the critical point of the evaporating surface can be written in the form of:

$$C_{hrw} = [1 - \psi_0(V)] C_{hr},$$

where $\psi_0(V)$ is the power function of the flight speed $V$: $\psi_0 = \alpha_0 V^{\beta_0}$ : (where $V$ is expressed in km/s, and $\alpha_0 = 0.0059$, $\beta_0 = 1.36$ for the air).

Statistics of meteorite falls show that a large part of them, including the ones considered in this work, hit the Earth’s surface broken to pieces, so the calculation of the entrainment mass requires consideration of their fragmentation.

We consider the process of meteorite fragmentation within the model of sequential fragmentation with the influence of scale factor on the tensile strength of the object. The model of sequential fragmentation of the body is based on the statistical theory of strength [8], when the fragmentation occurs at the defects and cracks that are inherent in such structurally heterogeneous bodies like meteorites. As a result, the fragmentation occurs as a process of successive elimination of defects with increased load followed by destruction of the body by these defects, thus the resulting fragments have greater strength than the original body. In this regard, the process of fragmentation ends when the velocity head starts to decrease. The detailed model of fragmentation is presented in the works [1, 9]. The problem of motion of disintegrating meteoroids is solved in three steps. On the first step we consider the motion of the monolithic body from the altitude of entry into the atmosphere before crushing, on the second – the movement of a swarm of fragments from the altitude of the beginning of fragmentation to the altitude of maximum velocity head. In the third step, since the fragments are considered to have the same size, the movement of a single fragment is tracked.

According to this model the strength of the fragment will take the following form:
\[ \sigma^*_f = \sigma_0 \left( \frac{M_0}{M_f} \right)^\alpha, \]  

(1)

where \( \sigma_0, M_0 \) are the tensile strength and mass of the meteoroid before entering the atmosphere, \( \sigma^*_f, M_f \) are the same characteristics for a fragment; \( \alpha \) is the indicator of heterogeneity of the material (larger \( \alpha \) means greater heterogeneity).

The condition of the beginning of the destruction of the bolide in the atmosphere is:

\[ \rho \nu^2 = \sigma^*, \]  

(2)

where on the left is the magnitude of the velocity head, \( \sigma^* \) is one of the strength characteristics of the material of the meteoroid (compressive, tensile, shear).

The height of the beginning of fragmentation in the exponential atmosphere \( z_* \) is determined assuming that at this point, the body does not have time to decelerate and its speed is the initial speed of atmospheric entry \( \nu_0 \):

\[ z_* = h \ln \left( \frac{\rho \nu_0^2}{\sigma^*} \right) \]  

(3)

From this height, instead of a single body a swarm of fragments is falling, with increasing number \( N \).

Assuming that the resulting fragments of the sphere of equal mass \( M_f \) (\( M_f = \frac{M}{N} \)), from (1-3) is obtained, their number depend on the current values of dynamic pressure and the total mass of all fragments and the area of the Midsection (determined on the assumption that the fragments do not overlap):

\[ N = \frac{M \left( \frac{\rho \nu^2}{\rho \nu_*^2} \right)^{1/\alpha}}{M_* \left( \frac{\rho \nu^2}{\sigma^*} \right)^{1/\alpha}}; \quad S_{mid} = S_{mid*} \left( \frac{M \left( \frac{\rho \nu^2}{\rho \nu_*^2} \right)^{1/\alpha}}{M_* \left( \frac{\rho \nu^2}{\sigma^*} \right)^{1/\alpha}} \right) \]

3. The results of the calculations

In [10] the following observations of the Chelyabinsk meteorite are provided: the body flew into the Earth's atmosphere at an angle \( ~ 18^\circ \) to the horizon with a speed of \( ~ 19.2 \text{ km/s} \); the size of the meteorite \( ~ 19.8 \pm 4.6 \text{ m} \); the final explosion occurred at an altitude of about 23 km. The collected fragments were ordinary chondrite structures, the effective enthalpy of evaporation of such material is assumed to be \( H_{eff} = 8\text{ kJ/g} \). Body collapsed in several stages: the destruction began at an altitude of \( ~ 45 \text{ km} \). The value of the strength parameter corresponding to the altitude of beginning of fragmentation, in this case is \( \sigma_* = 10^6 \text{ N/m}^2 \). Assuming that the meteor is a ball of radius \( R \sim 9.8 \text{ m} \), and the characteristic chondrite density is \( 3.3 \text{ g/cm}^3 \), its mass would be approximately 13,000 tons. These data are used in this paper in the simulation of flight and destruction of the Chelyabinsk meteorite in the atmosphere.

Sikhote-Alin meteorite is a typical iron meteorite. Effective enthalpy of vaporization of iron is significantly below this value for a chondrite and is about 2 kJ/g. According to the description of eyewitnesses, the fiery iron rain fell on the forest of the Sikhote-Alin in Primorsky Krai of Russia, on 12 February 1947. Witnesses said that the bolide was brighter than the sun. The earth's atmosphere was invaded by a space body several meters in diameter and weighing hundreds of tons. The fall of the meteorite occurred at an angle of \( 41^\circ \). When moving through the atmosphere it experienced repeated fragmentation. The first fragmentation occurred at an altitude of about 58 km [11]. According to these data, the critical value of the strength parameter, which begins the process of fragmentation is estimated to be \( 10^5 \text{ N/m}^2 \).

Beneshov bolide was one of the most striking meteoroids, the speed at which the entry was made being over 21 km/s. The separation of fragments from the main body was observed at the height of 42 km. The final extinction of the bolide occurred at an altitude of 19 km at a speed of compact swarm of
debris - 5.2 km/s [12]. Twenty-three years scientists could not find the fragments of the meteorite, but thanks to modern techniques and more accurate calculations, was 4 pieces were discovered, with a total mass of approximately 12 kg. The estimated initial mass of the meteoroid Beneshov amounted to 2 - 4 t [12]. Meteorite Kunya-Urgench had the initial mass about the same as meteorite Beneshov, about 3 t. It flew into the atmosphere at a speed of 13 km/s at an angle of 30° to the horizon. According to the observations, the height of the beginning of the fragmentation was ~ 25 km, the explosion occurred at an altitude of 10-15 km, after which the meteorite began to fall almost vertically [13]. The largest part of the meteorite, weighing 820 kg, fell in a cotton field, forming a crater with a diameter of about 5 meters. Fig. 1 shows the heat transfer parameters for all of these meteorites depending on the flight altitude H, calculated in the framework of a single-body model (excluding fragmentation).

Figure 1. The values of convective and radiative transfer at the critical point depending on the height of the flight of meteorites: a - Chelyabinsk; b – the Sikhote-Alin, c - Beneshov, d - Kunya-Urgench.
The calculation of parameters of heat exchange conducted in the framework of the model show that for Chelyabinsk and the Sikhote-Alin meteorites the radiation heat flux is far superior to the convective one almost all the way down (high speed flight and large body size). While for a meteorite like Kunya-Urgench (small speed of flight and small body size) the values of radiative heat flux are several orders of magnitude lower, only at altitudes of 50-20km there is a slight predominance of the radiant flux over the convection. For the Beneshov meteorite with a size comparable to Kunya-Urgench, on the contrary, radiative heat transfer dominates the convective, mostly because of the high speed flight.

Change of the total mass of meteoroids depending on the altitude in the model of a single body and a disintegrating body is shown in Fig. 2. It should be noted that ablation of mass at first increases dramatically due to the increase in surface area in the fragment stream. But this leads to increased suppression of the fragmentation of the body, leading to decreased velocities of the meteoroid and its fragments, which in turn reduces the heat flow to the surface and slows down the process of ablation. Therefore, the result of the entrainment of its mass compared to a non-fragmented bolide is unclear, as illustrated by the data in Fig.2.

The data in Fig.2 shows different values of the parameter $\alpha$ characterizing the degree of heterogeneity of the material. The number of the generated fragments strongly depends on the value of the parameter. For example, the Chelyabinsk meteorite with $\alpha = 1/2$ has the number of fragments $N \sim 233$, while $\alpha = 1/8$ corresponds to $N \sim 185900$; for the Sikhote-Alin fireball when $\alpha = 1/4$, the number of fragments is the order of $2 \cdot 10^5$. For bolide Beneshov the number of slices varies from 8 to 228 when the parameter $\alpha$ is $4/5$ to $1/4$, and for meteorite Kunya-Urgench from 2 to 6, with $\alpha$ changing from $1/2$ to $1/8$. The strength of meteoroids varies widely: $10^5$-$10^7$ N/m$^2$. Usually little bodies are more uniform than large, the critical strength parameter is higher, so the number of generated fragments $N$ is small.

It should be noted that according to Fig.2 the total mass of the fragments of the considered meteorites is much higher than the observed data. For instance, the weight of the found fragments of the Chelyabinsk meteorite does not exceed 1T, about 1T in the case of meteorite Kunya-Urgench, while for meteorite Beneshov it is negligible - not more than 12 kg. After the fall of the Sikhote-Alin bolide tens of thousands of fragments were collected with a total weight of about 27 tonnes.
Figure 2. The change of the total mass of meteoroids depending on altitude for different values of parameter α. a – Chelyabinsk meteorite; b – Sikhote-Alin, c - Beneshov, d - Kunya-Urgench.

However, during the research it was found that at the final stage of the movement of meteoroid, destruction process can continue due to the thermal stress. Thermal stresses do not play a big role for large meteoroids, but if the size of the chunks reaches several centimeters, the resulting temperature gradients can break them into further small pieces to the size of coarse dust, which rapidly melts and evaporates in high temperature air. The complexity of the considered mechanism of fragmentation of meteorites is also demonstrated by evidence given in [10]. Lots of small (no larger than 2 cm) fragments of the Chelyabinsk meteorite were found over an extensive area. Among the collected cm of debris there were pieces with partial crust melting, which suggests that the split continued after the loss of meteor speed, and this process is caused by thermal stresses resulted in an additional mass loss. In [14] the evaluation showed that for bodies of 10 cm radius the time to reach the critical stress is ~ 4s. This means such a body during the fall through the atmosphere may be subjected to destruction due to thermal stress for several times. This mechanism may explain, for example, why the many tons of the Chelyabinsk meteorite were disintegrated into many small fragments. Simultaneously with ablation, an other intensive meteorite destruction process can join in the so called Gertler vortexes. They arise in the boundary layer of the flow near the surface defects and present plasma microvortexes spinning at great velocities. The vortexes literally "bite" into the surface of the meteorite and "drill" her to deepen regmaglypt, which in turn stimulates the release of small fragments, which quickly decelerate in the atmosphere, fail to fully evaporate, and then fall as meteorites to the Earth along the flight path of the fireball.

It is confirmed that the possible fragmentation of medium-sized meteorites does not always influence its trajectory. For example, when observing and registering the meteoroid in Beneshov, the photos clearly showed fragmentation of meteoroids: it was a movement of 8 fragments before the final destruction. But according to observers [15] the mass of the separated fragments was much lower than initial body weight. In [16] it is shown that the trajectory of the fireballs is not determined by the model of progressive fragmentation, which involves the destruction of approximately equal fragments, and depends mainly on ablative processes. In this regard, for an approximate description of the trajectories and parameters of the Beneshov bolide the single-body model is more suitable, it gives the final mass of the meteorite closer to reality.

One of the important characteristics in meteor physics is the loss of kinetic energy of a body per unit length depending on the altitude. Suppression of meteorite fragmentation at the stage of falling leads to consequences such an explosion – an instantaneous release of energy at some point of the trajectory. In meteor physics an "explosion" of the meteoroid in flight is a rapid loss of kinetic energy of the body with its transition into the kinetic and internal energy of the surrounding gas.
Given the equations of the system (1) one can determine the energy released in the atmosphere, taking it equal to the loss of kinetic energy of the body \( E \):

\[
\frac{dE}{dz} = \frac{S_{mid} \rho V^2}{2 \sin \theta} \left( C_D + C_H \frac{V^2}{2H_{eff}} \right)
\]

Fig. 3 shows the calculated curves of the kinetic energy losses per unit length calculated for the considered bodies with and without fragmentation at various values of the parameter \( \alpha \). It is clear that the maximum energy loss, the so-called explosion, for the Chelyabinsk meteorite occurs at 12 km height when using the model of a unified body, and at 20-35 km when fragmentation model is used. The strength parameter \( \alpha \) was changed form 1/2 to 1/8 (observations note the height of the main explosion, is equal to 23 km).

**Figure 3.** The loss of kinetic energy per unit length depending on flight height with different values of scale parameter for meteorites:

- a – Chelyabinsk meteorite; 1 – a single body, 2 – disintegrated meteorite, \( \alpha=0.5 \), 3 – disintegrated meteorite, \( \alpha=0.25 \); 4 – disintegrated meteorite, \( \alpha=0.125 \).
- b – Sikhote-Alin meteorite; 1 – a single body, 2 – disintegrated meteorite, \( \alpha=0.25 \).
- c – Beneshov meteorite; 1 – a single body, 2 – disintegrated meteorite, \( \alpha=0.8 \), 3 – disintegrated meteorite, \( \alpha=0.5 \), 4 – disintegrated meteorite, \( \alpha=0.25 \).
- d – Kunya-Urgench meteorite, 1 – single body, 2 – disintegrated meteorite, \( \alpha=0.25 \).
For the Sikhote-Alin meteorite the calculated curve in Fig.4b, corresponds to fragmentation with the strength parameter $\alpha = 0.25$, has a maximum height of $H = 33\text{km}$. In this case, the meteor body splits into many fragments ($\sim 2 \cdot 10^5$). For Beneshov meteorite the single-body model most correctly reflects the trajectory of the meteorite, gives the height of the explosion, equal to 23 km, which roughly corresponds to the observed height (24 km). The maximum energy loss for the meteorite Kunya-Urgench estimated to occur at a height of 15-18 km, which is also close to the observation data (10-15 km).

Thus, understanding the processes of destruction of meteoroids in the atmosphere appears to be extremely important: it can give more information about the structure of natural space bodies and contribute to the creation of new models for predicting the movement and destruction of meteoroids.

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