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The Effect of Ballistic Parameters of Meteoroids on Their Destruction in the Earth's Atmosphere

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Abstract—The problems of the motion and destruction of large cosmic bodies under the influence of thermal and force loads in the Earth's atmosphere are considered. Based on the modified physical theory of meteors, a mathematical model of the trajectories of the motion of such bodies during the penetration of the planet's atmosphere is constructed. A computational experiment is carried out for known meteoroids selected as the reference ones in order to determine the effect of the ballistic parameters of the entry of these meteoroids (the angle of inclination of the trajectory to the Earth's surface and velocity) on the process of their destruction in the Earth's atmosphere. It is shown that these characteristics have a significant influence on the motion and destruction of cosmic bodies.

Keywords: meteoroid, heat flow, entry parameters, destruction, ballistics

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1. INTRODUCTION

The initial stage of meteoroid entry into the upper rarefied layers of the atmosphere is accompanied by a combined effect of radiative and convective heat fluxes on it, leading to a strong—up to tens of thousands of degrees—heating of the gas at its surface, which begins to glow (bolide effect), and ablation of the material of the meteoroid. When moving in the lower dense layers of the atmosphere, a sharp deceleration of the body occurs due to the significant increase in the velocity pressure. The occurrence of significant overloads under the influence of high mechanical and thermal stresses, as well as ablation, most often lead to the complete or partial destruction of the meteoroid, depending on its size, strength, and speed. In this paper, we consider the influence of the ballistic parameters of the entry of large celestial bodies (the angle of inclination of the trajectory to the Earth's surface and velocity) on the process of their destruction in the Earth's atmosphere.

The motion and process of destruction of meteoroids that differ from each other in parameters of entry into the atmosphere are analyzed. The results of numerical studies of the motion and destruction in the Earth's atmosphere of two well-known meteoroids—Benešov [1] and Kunya-Urgench [2]—bodies of the same size and initial mass, but significantly different in velocity and angle of entry into the atmosphere, are presented. We also present the results of calculating the motion and destruction of a larger meteoroid (the size and entry velocity of which presumably correspond to the Tunguska meteoroid [3]) when varying the angle of entry into the atmosphere.

2. BASIC EQUATIONS

Changes in the velocity V, mass M, and angle of inclination of the velocity vector to the horizon θ of a meteorite are described by the equations of the physical theory of meteors [4]:

$$M\,dV/dt = Mg\sin\theta - C_D S\rho V^2/2, \tag{1}$$

$$MV\,d\theta/dt = Mg\cos\theta - MV^2\cos\theta/(R_E + z) - C_N S\rho V^2/2, \tag{2}$$

$$H_{\text{eff}}\,dM/dt = -C_H S\rho V^3/2, \tag{3}$$

$$dz/dt = -V\sin\theta. \tag{4}$$

Here, C_D, C_N, and C_H are the coefficients of drag, lift, and heat transfer to the body's surface, respectively; S is the body's cross-sectional area; R_E is the radius of the Earth; H_{eff} is the effective enthalpy of vaporization of the meteorite material; and z is the height of the meteoroid above the Earth's surface. The change in the air density ρ with height z is given by the formula

$$\rho = \rho_0 \exp(-z/h), \tag{5}$$

where ρ_0 is the atmospheric density at $z = 0$ and h is the characteristic scale of the height.

The midsection area S in generally variable, since the mass of a meteoric body changes with height:

$$S_e/S = (M_e/M)^{\mu}. \tag{6}$$

Index e corresponds to the parameters of the body entering the atmosphere. The value of parameter μ characterizes the effect of the change in the shape of the body due to the removal of its mass. At $\mu = 2/3$ entrainment occurs evenly over the entire surface and the shape factor of the body is preserved. A necessary condition for this is the rapid and chaotic rotation of the meteoroid, which ensures the uniform removal of mass from the entire surface. In the other limiting case—oriented motion without rotation—the maximum heating, and, consequently, the entrainment of mass occurs in the vicinity of the critical point of the body. This case is equivalent to the assumption of a constant midsection, i.e., $S = \mathrm{const}$ and $\mu = 0$.

To calculate the motion of meteoroids in the lower layers of the atmosphere, it is necessary to take into account the change in body mass. In a high-temperature gas flow, two mechanisms of heat transfer from the gas to the surface of the body take place: convective heat transfer and heat transfer by radiation.

For the convective heat flux at the critical point of the meteorite spherical surface, the following formula is used [5]:

$$q_{k0} \approx 3.3\times 10^{-5}(\rho_\infty/R)^{1/2}V_\infty^{3.2},\ \mathrm{W/m^2}.$$

Here, R is in m, ρ_∞ is in kg/m^3, and V_∞ is in m/s. Index ∞ corresponds to the oncoming flow parameters.

For the radiative heat transfer coefficient at the critical point, the ReVelle formula is used, whose parameters are presented in [6]:

$$C_{Hr} = f\cdot e^{A_1}\rho^{A_2+A_3V-1}R^{A_4+A_5V+A_6V^2}V^{A_7+A_8V+A_9V^2-3}.$$

Here, A_i are the numerical coefficients determined experimentally. Accordingly, the heat flux at the critical point will be written as

$$q_{r0} = 0.5\rho_\infty V_\infty^3 C_{Hr}.$$

The total heat flux to the body surface is defined as $q = q_k + q_r$.

3. FRAGMENTATION OF METEOROID

The statistics on the fall of meteoroids show that most of them fell to the Earth as crushed fragments; thus, the calculation of mass entrainment requires taking into account the process in which they are crushed. There are many theoretical models of meteoroid fragmentation (see, for example, [7]).

A cosmic body can collapse into several large fragments, which then fly autonomously, or break up into a cloud of small fragments, united by a common shock wave, and fly in the form of a cluster as a whole. This cloud usually expands rapidly and slows down during flight, causing a bright burst of radiation. During the destruction of a large meteoroid, both of these scenarios of fragmentation can occur simultaneously.

In this paper, the process of meteoroid fragmentation is considered in the progressive fragmentation model, taking into account the influence of the scale factor on the ultimate strength of the object. The statistical theory of strength is used [8], when it is assumed that fragmentation occurs along defects and cracks, which are inherent in structurally inhomogeneous bodies such as meteoroids. However, fragmentation is presented as a process of the successive elimination of defects with an increase in the force load by the destruction of the body along these defects. Fragments appearing in this way are stronger than the original body. The fragmentation process will end as soon as the velocity head starts to decrease [9, 10]. In this case, the fragment strength is written as

$$\sigma_f^* = \sigma_e(M_e/M_f)^{\alpha}, \tag{7}$$

where σ_e and M_e are the tensile strength and mass of the meteoroid upon entry into the atmosphere, σ_f^* and M_f are the same characteristics for the fragment; and α is the indicator of the degree of heterogeneity of the material. At $\alpha \to 0$, the meteoroid breaks up into tiny fragments that move in the hydrodynamic regime, as described, for example, in [11]. For large values of α, fragmentation will not occur, and the body will move as a whole. The values of parameter α for stony meteoroids, as a rule, are in the range of 0.1–0.5 [7].

The behavior of a celestial body depends on the ratio of its strength characteristics (for compression, tension, shear) and the velocity head, which monotonically increases with the decreasing flight altitude to its maximum value.

The condition for the start of the destruction of the fireball in the atmosphere is as follows:

$$\rho_* V_*^2 = \sigma^*, \tag{8}$$

where the magnitude of the velocity head is on the left and one of the strength characteristics of the meteoroid material σ^* is on the right. If the velocity head does not reach value σ^*, then the celestial body passes through the atmosphere without going through the crushing process.

The height z_* at which crushing starts in an exponential atmosphere is defined as

$$z_* = h \ln(\rho_* V_*^2 / \sigma^*). \tag{9}$$

The parameters with an asterisk refer to the start of the crushing process. If we consider the model of progressive crushing, then, starting from this height, instead of a single body, a swarm of crushing fragments with an ever-increasing number N of fragments falls, whose strength depends on their mass M_f according to law (7). Assuming that the resulting fragments are spheres of the same mass M_f ($M_f = M/N$), their number is obtained from Eqs. (7)–(9) depending on the current values of the dynamic pressure and the total mass of all fragments

$$N = \frac{M}{M_*}\left(\frac{\rho V^2}{\rho_* V_*^2}\right)^{1/\alpha} = \frac{M}{M_*}\left(\frac{\rho V^2}{\sigma^*}\right)^{1/\alpha}. \tag{10}$$

When considering the motion of a swarm of fragments, its effective midsection area depends on the number of fragments formed. If we assume that the resulting fragments of the same mass do not overlap, then to determine the effective area of the midsection of their swarm, we obtain

$$S = S_* \frac{M}{M_*}\left(\frac{\rho V^2}{\rho_* V_*^2}\right)^{1/3\alpha}. \tag{11}$$

In other words, according to this model, starting from the height z_*, a swarm of fragmented fragments will move, surrounded by a common shock wave, with a progressively increasing number of fragments. Therefore, when studying the ballistics of a swarm of fragments, we can use the equations of motion as a single body, but with a variable midsection area determined by formula (11).

The problem of the motion of a meteoric body that is being crushed is solved in three stages. At the first stage, the motion of a single body from the height of entry into the atmosphere to the height of the start of crushing is considered; at the second stage, the motion of a swarm of fragments from the height of the start of crushing to the height of the maximum velocity head; and at the third stage, at the end of the crushing process, it is considered that the fragments move independently and the motion of one fragment is considered, since it is assumed that they are all of the same size.

4. RESULTS AND DISCUSSION

The results of the numerical studies of the motion and destruction in the Earth's atmosphere of two meteoroids, Benešov (1991) and Kunya-Urgench (1998), of the same size and composition (stone chondrites) but differing in their atmospheric entry parameters are presented.

The Benešov bolide (1991, Czech Republic) was one of the brightest bolides moving at an approximate velocity of 21 km/s on entry at an angle of 45° into the atmosphere [12]. Its fragmentation was recorded starting from a height of 42 km. As the observational data showed, in the altitude range of 24 km < z < 42 km, relatively small fragments were separated from the main body (Fig. 1). At an altitude of 24 km, the

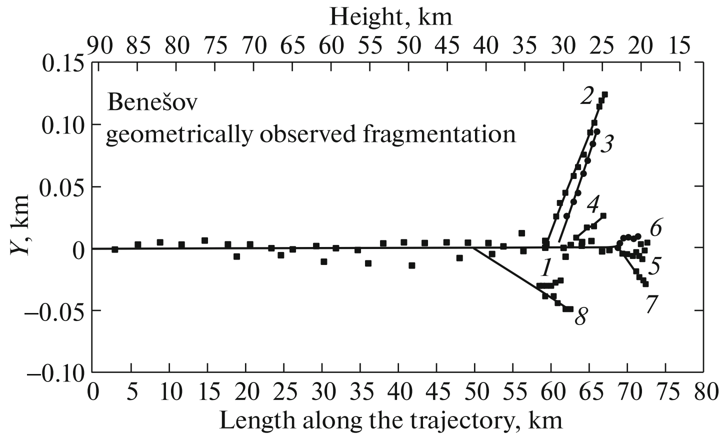

Fig. 1. Scheme of the dispersion of fragments of the Benešov bolide; Y is the lateral deviation; (*1–8*) are numbers of observed fragments [1].

bolide finally disintegrated into three large and many small fragments, and their complete extinction took place at a height of ~19 km at a velocity of this compact swarm of fragments of 5.2 km/s [1].

Only twenty years later, in 2011, thanks to modern search methods and more accurate calculations, four small meteorite fragments of the Benešov bolide were found [13]. Its initial mass was estimated to be ~three tons. The photographs of the fall of the Benešov bolide made it possible to clearly trace the crushing process: the motion of eight of its fragments until the final disintegration was recorded. However, according to observers, the mass of the separated fragments was much smaller than the initial mass of the body. It was shown in [14] that the trajectory of the Benešov bolide did not correspond to the model of progressive fragmentation, which assumes destruction into approximately identical fragments, but mainly depends on ablation processes. Thus, the model of a single ablation body turned out to be more suitable for simulating the trajectory and parameters of the Benešov bolide. The trajectories and mass loss calculated in this study with and without fragmentation confirmed that the single-body model gives trajectory parameters and final masses that are closer to observations and the found mass of meteorites.

The Kunya-Urgench meteoroid also had an initial mass of ~three tons, but it entered the atmosphere at a velocity of 13 km/s at an angle of 30° to the horizon [2]. According to the observational data, the fragmentation started at an altitude of ~25 km, and the explosion occurred at an altitude of 10–15 km, after which the fragments of the bolide began to fall almost vertically. The largest part of the meteorite, the parent body of the meteoroid weighing 820 kg, fell into a cotton field, forming a funnel about 5 m in diameter. The total mass of fragments of the meteorites that fell was ~1 t.

Thus, it was found that the studied meteoroids, identical in mass, composition, and size, moved and broke up in the atmosphere in completely different ways. To explain this, we should consider the calculated parameters of heat transfer to the surface of bodies depending on the flight altitude (see Fig. 2). Due to the difference in entry velocities and angles of entry into the atmosphere, the radiative heat flux to the surface of the Benešov bolide was two orders of magnitude higher than the corresponding flux to the surface of the Kunya-Urgench bolide. As a result, a more intense ablation process in the former led to a significantly greater loss of mass when moving in the Earth's atmosphere (Fig. 3). According to the calculations, it turned out that the final mass of the Benešov meteorite was 10% of the initial one, and that of the Kunya-Urgench meteorite was 80%. Thus, the results of the calculations proved once again that each meteoroid is fundamentally individual and the study of the motion and destruction of each specific meteoroid is a purely independent task.

Note that the calculated total mass of the fallen fragments of these meteoroids is much higher than the observational data. This can be explained by the fact that at the final stage of the motion of meteoroids, the process of destruction of centimeter-sized meteoroid fragments can continue due to thermal stresses [15]. Moreover, simultaneously with ablation, another factor that destroys the meteoroid, the effect of the so-called Gortler vortices, can come into play [16]. They arise in the boundary layer of the oncoming flow near the body's irregularities. These vortices literally dig into the surface of the meteoroid and drill out recesses in it: regmaglypts. This, in turn, contributes to a massive ejection of small fragments to the sides,

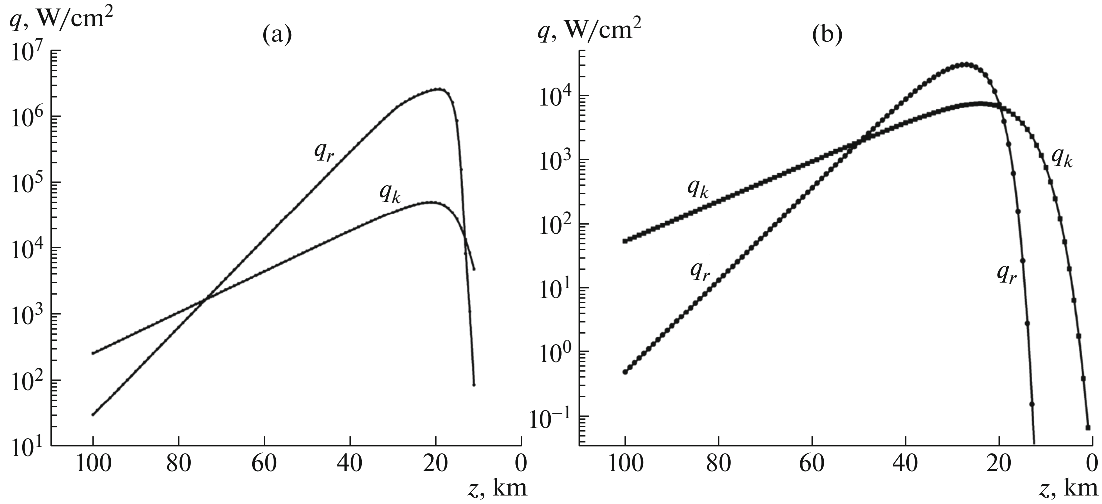

Fig. 2. Values of convective (q_k) and radiative fluxes (q_r) at the critical point depending on the flight altitude z for meteoroids: (a) Benešov and (b) Kunya-Urgench.

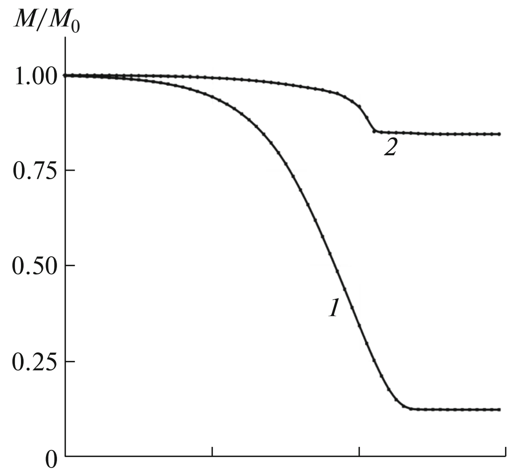

Fig. 3. Relative change in the mass of meteoroids along the trajectory: (*1*) Benešov and (*2*) Kunya-Urgench.

which quickly slow down in the atmosphere and, if they do not completely evaporate, then they fall out as small meteorites onto the Earth's surface along the flight path of the meteoroid.

As an example, the motion and destruction in the Earth's atmosphere of a much larger meteoroid with a mass of $M = 10^6$ T at a velocity of 30 km/s (the size and velocity of entry presumably correspond to the Tunguska body) at different angles to its surface was also calculated. It has been established that the number of fragments formed during the crushing of a meteoroid and the total mass of its fragments significantly depend not only on the strength characteristics of the meteoroid but also on its ballistic parameters.

If we consider the problem in the approximation of a single body (without taking into account fragmentation), then the data presented in Fig. 4 show how the flight altitude of such a meteoroid changes depending on time for different angles of its entry into the atmosphere. It can be seen from the calculation graphs that with $\theta_e > 9°$ a meteoroid with such defining parameters will fall into the Earth, and when $\theta_e \leq 9°$, starting from a certain height, its trajectory becomes ascending. According to the configurations of the curves presented in Fig. 4, it can be seen that the flight trajectories significantly depend on this parameter θ_e. At $\theta_e \leq 9$ the inclination angle of the trajectory changes sign over time and its final segment becomes ascending. We call such trajectories transient. Moreover, the smaller the value of this parameter the earlier the sign changes. Thus, for $\theta_e = 5°$, $7°$, and $9°$, the transition to the ascending branch of the

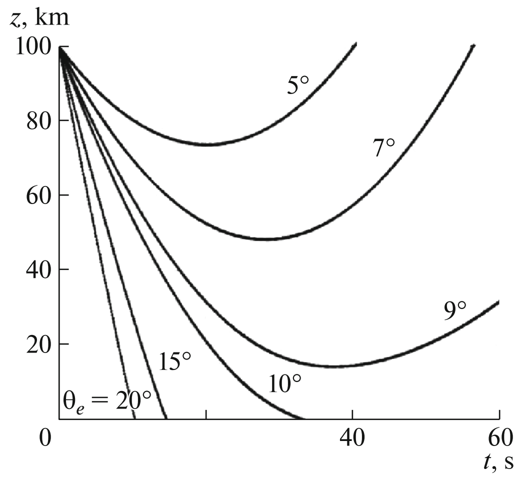

Fig. 4. Dependence of flight altitude z on time t for different entry angles θ_e.

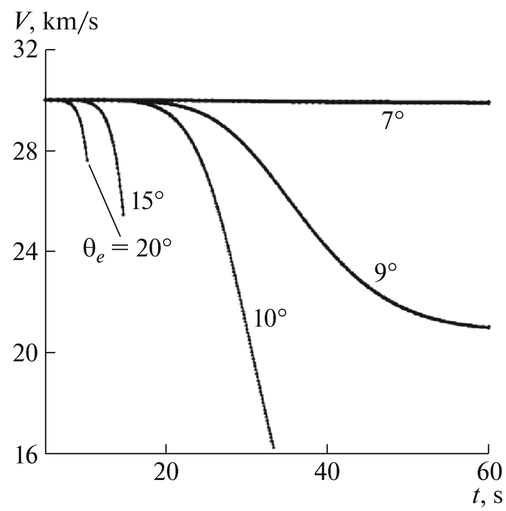

Fig. 5. Change in the speed of a meteoroid depending on the time of flight t for different entry angles θ_e.

trajectory is realized for the time values t = 20, 30, and 40 s, respectively. At the initial entry angles of $\theta_e > 10°$, there is a hard collision of meteoroids with the Earth's surface at a sufficiently large angle. This can lead to tragic consequences for objects and the population in the vicinity of the point of impact, depending on the speed of the fall.

It can be seen from the graphs in Fig. 4 that in the cases of transient trajectories at small entry angles to the atmosphere (θ_e = 5°–7°) meteoric bodies do not enter the dense layers of the atmosphere at all, but penetrate the upper layers of the atmosphere in the free molecular flow mode, without experiencing practically any environmental resistance and, as the calculations show, do not lose their speed (Fig. 5) or mass.

Note that the critical value of the entry angle for the model of a single body $\theta_e = 9°$ at which the trajectories become transient is also confirmed by the estimates given in [17]. Let us analyze in more detail the gentle trajectory of a large meteoroid in the Earth's atmosphere, taking into account the results of this study. The change in the angle of entry of the body into the atmosphere is represented by Eq. (2). In [17] the processes of thermal ablation and fragmentation of the meteoroid are not considered and it is assumed that the body has a spherical shape, i.e., $C_N = 0$. Then for an gentle trajectory of $\cos(\theta) \approx 0$ and the equation of motion (2) will be written in the following form:

$$d\theta/dt = g/V - V/R_E. \tag{12}$$

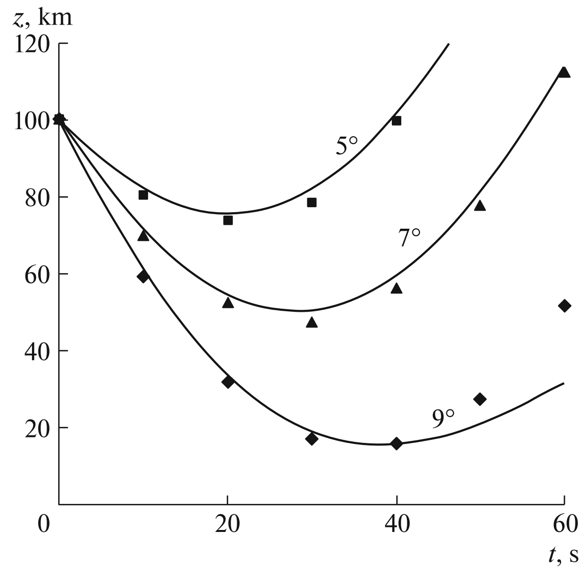

Fig. 6. The change in the flight altitude of a body depending on the time for $\theta_e = 5°, 7°, 9°$ and entry velocity $V_e = 30$ km/s.

Further, it is assumed that at altitudes above 40 km, the right side of the equation of motion (1) is negligible; thus, the velocity is constant and equal to the entry velocity $V = V_e$.

Note that the right side of Eq. (12) vanishes when $V_e = 8$ km/s, i.e., at an entry velocity close to the first cosmic velocity. With an increase in V_e, the second term on the right side of Eq. (12) increases and the first one decreases, and the angle of inclination of the trajectory in this case is not constant; i.e., the body does not move in a straight line. In [17], Eqs. (12) and (4) are integrated. Taking into account the small value of the entry angle, the following analytical dependences are obtained for changing the angle of inclination of the trajectory to the Earth's surface and height on the flight time of the body:

$$\theta = \theta_e + (g/V - V/R_E)t, \tag{13}$$

$$z = z_e - V_e\theta_e t + at^2/2, \quad a = V_e^2/R_E - g. \tag{14}$$

The results of calculating the trajectory of the body according to formula (14) at the speed of the body's entry $V_e = 30$ km/s and entry angles of $\theta_e = 5°$, 7°, and 9° are presented in Fig. 6 (squares, triangles, and rhombuses, respectively). The results of the numerical integration of the system of Eqs. (1), (2), and (4) are also presented here without taking into account ablation and fragmentation (solid lines).

The graphs in Fig. 6 show good agreement between the exact numerical and approximate solutions for the entry angles $\theta_e = 5°$ and 7° and the divergence of the results on the ascending branch of the trajectory at $\theta_e = 9°$. Apparently, this is explained by the fact that, for this entry angle, the body is moving in fairly dense layers of the atmosphere, where it noticeably slows down; therefore, the condition of constancy of the velocity in the approximate dependences [17] for $\theta_e = 9°$ is a rough approximation.

Accounting for the fragmentation process of the considered stony meteoroid leads to a decrease in the critical value of the entry angle: $\theta_e = 8°$ [18]. The calculations show that such a body at $\theta_e = 8°$, at some point in time, changes the mode of its motion in the atmosphere from descending to ascending and goes back into outer space. At the same time, it does not reach the lower dense layers of the atmosphere and barely loses its speed or mass.

The variation of the angle of entry for the same body affects the process of its fragmentation. Table 1 shows the maximum number of generated fragments N_{max} for different angles θ_e of entry at an entry speed of $V_e = 30$ km/s for meteoroid tensile strengths of $\sigma^* = 10^6$ N/m^2 and $\sigma^* = 10^7$ N/m^2, which corresponds to stone bodies.

Naturally, for a more durable meteoroid ($\sigma^* = 10^7$ N/m^2), the number of formed fragments is 1–3 orders of magnitude less than in the case of a more brittle body ($\sigma^* = 10^6$ N/m^2). With oblique trajectories of the body, there are significantly fewer fragments compared to its steeper trajectories. This is due to the

Table 1. Maximum number of fragments for different entry angles for $\sigma^* = 10^6$ N/m^2 and $\sigma^* = 10^7$ N/m^2 at a velocity of $V_e = 30$ km/s

θ_e, deg	30	15	9	8
N_{max}, $\sigma^* = 10^6$ N/m^2	2.88×10^5	7.53×10^4	1.1×10^4	1.9×10^3
N_{max}, $\sigma^* = 10^7$ N/m^2	6.2×10^3	1.47×10^3	126	2

Table 2. Meteoroid L's flight range depending on entry angle θ_e

θ_e, deg	20	15	10	9	7	5
L, km	293	424	921	2207	1686	1205

fact that when the body moves at a small angle to the Earth's surface, the fragmentation process slows down: the increase in the velocity pressure is smoother than with steep trajectories, and the appearance of new fragments, according to the fragmentation model under consideration, depends significantly on the value of the velocity pressure. Figure 7 shows the change in the mass of a fragmenting meteoroid for three values of the angle of entry of the body into the atmosphere: 60°, 15°, and 9°.

It should be noted that during the fragmentation of a meteoric body, the amount of mass loss can increase sharply due to the increase in the surface area in the stream; therefore, when $\theta_e = 30°$, when a large number of fragments are formed during the motion of the body, its final mass is approximately an order of magnitude less than, for example, when $\theta_e = 15°$.

The flight range of meteoroid L for different entry angles θ_e into the atmosphere is presented in Table 2. For flight paths, the range is calculated along the surface of the planet from the projection onto it of the point of entry of the body into the atmosphere to the projection of its exit point at height z = 100 km; and for the rest, from the projection of the point of entry of the body into the atmosphere onto it to the point of impact of the body.

If the velocity of entry of a meteoroid into the Earth's atmosphere is significantly slower than the considered $V_e = 30$ km/s, then even at small entry angles ($\theta_e < 8°$), it can reach the dense layers of the atmosphere, slow down to a velocity less than the first cosmic velocity, and eventually fall to the Earth. The data

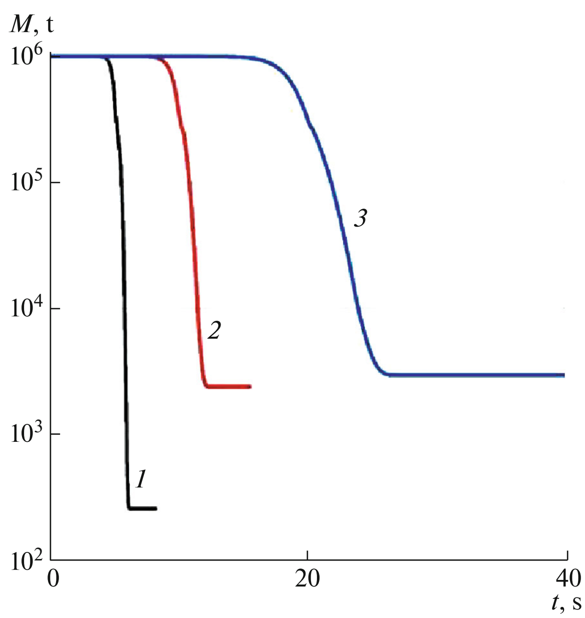

Fig. 7. Change in the mass of a fragmenting meteoroid at different angles of entry into the atmosphere: (*1*) 30°; (*2*) 15°; (*3*) 9° ($\sigma^* = 10^6$ N/m^2).

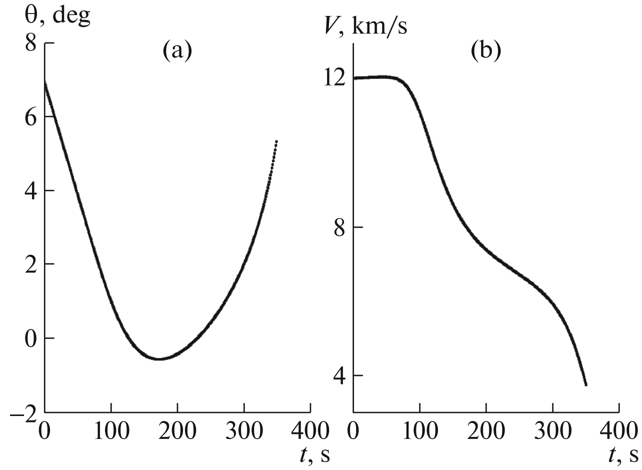

Fig. 8. Dependencies of the angle of inclination of trajectory θ (a) and velocity of motion V (b) of meteoroid on flight time t for body weight $M = 1 \times 10^6$ t at $V_e = 12$ km/s and $\theta_e = 7°$.

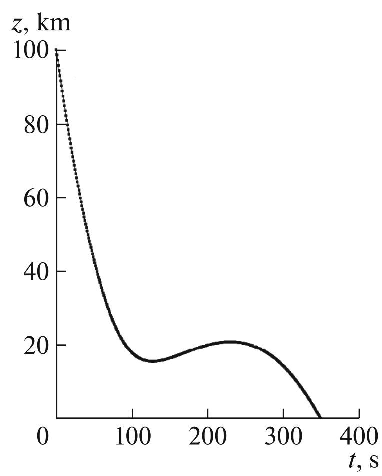

Fig. 9. Dependence of flight altitude z on flight time t for body weight $M = 1 \times 10^6$ t at $V_e = 12$ km/s and $\theta_e = 7°$.

for calculating the motion of such a body at the initial velocity $V_e = 12$ km/s and angle of entry into the atmosphere $\theta_e = 7°$ for a large meteoroid of mass $M = 10^9$ kg are shown in Figs. 8 and 9. From the graphs in Fig. 8, it can be seen how the angle of inclination of the trajectory decreases with time, and at some point its value becomes negative, and the trajectory is ascending; however, then the reverse process occurs—the angle of inclination of the trajectory grows to positive values and, as a result, its trajectory ends on the Earth's surface. Moreover, the velocity of the body near the surface becomes less than 4 km/s.

At small entry angles, the trajectories of cosmic bodies at which a soft landing occurs were also calculated, when, on the one hand, the body decelerated strongly during its long-term motion in the troposphere, and, on the other hand, the final segment of its fall turned out to be almost parallel to the Earth's surface. The famous Goba meteorite (60 tons) in South Africa, which did not leave any noticeable trace when it slid along the Earth's surface, is an example of such a soft landing [19].

CONCLUSIONS

A numerical experiment was carried out, which showed the decisive influence of the parameters of the entry of a meteoric body into the atmosphere on the processes of its motion and destruction. On the example of two well-known meteoroids—Benešov and Kunya-Urgench—of the same composition, mass, and size, but which differed in terms of their velocity and angle of entry, it was shown that while the former was almost completely destroyed in the atmosphere, the process of the motion of the latter is characterized by a rather large fragment (~1 t) falling out from it and the formation a very large crater on the surface of the Earth. The motion in the Earth's atmosphere of a much larger body with a mass of $M = 10^9$ kg, which entered it at a velocity of 30 km/s (its size and entry velocity presumably correspond to the characteristics of the Tunguska body) at different angles to its surface, is also considered. Depending on the angle and velocity of entry into the Earth's atmosphere, different scenarios of the body's motion are possible: (1) at angles ≤8°, through trajectories are possible, when the body penetrates the Earth's atmosphere and again goes back into outer space, or its fragments can be scattered along the flight trajectory far from the intended place of impact; (2) at angles >8°, fragments fall onto the Earth's surface; and their number and total mass also depend on the value of this angle.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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