Chapter 2
Aspects of Meteoroids Flight in the Earth's Atmosphere

Nina G. Syzranova and Viktor A. Andrushchenko

Abstract We study the motion of meteoroids in the Earth's atmosphere. It is shown that space bodies do not always fall on the Earth or explode and shatter into small fragments in the atmosphere. Instead, for certain aerodynamic characteristics and small angles of entry into the atmosphere, they may re-enter the outer space after traveling several thousand kilometres through the atmosphere.

2.1 Introduction

When space bodies pass into the Earth's atmosphere and move in it, various scenarios are possible. Large bodies (size greater than 100 m) usually reach the Earth's surface without losing much of their speed, forming impact craters, and can lead to catastrophic consequences. Small bodies (size less than 1 cm) burn completely at very high altitudes. Bodies of intermediate sizes are destroyed and burned at heights of ~20–40 km, causing bright flashes or exploding, breaking into fragments, forming shock waves and clouds of combustion products. Of particular interest are cases when meteor bodies or their fragments after the initial stage of falling in the atmosphere then go on an upward trajectory, and, only partially destroyed, return back to outer space. That is why, even when seismic effects appear as if from a fall, but in fact from the impact of an air explosion of meteoroid fragments, search expeditions often do not detect any impact craters or fallen meteorite matter.

Thus, on August 10, 1972, a flight through the atmosphere of a bright bolide detected by satellites of the US Air Force was registered [1]. Experts noted an unusually long flight path of the bolide in the atmosphere (about 1500 km). Witnesses even heard the thunderous sounds that indicated a low path of movement of the object.

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Everything pointed to the fact that the object was supposed to descend and fall to the ground, but its fall was never registered. This happened because the body was flying at a slight angle to the Earth's surface and "bounced" from the layers of the atmosphere, returned back to outer space [1, 2]. Estimates made in [3] show that such an intrusion into the atmosphere occurs quite rarely, and even more rarely, about once a century, such phenomena are observed. It is possible that such a meteor body was Tunguska (1908), the dynamics of which in the atmosphere is still a big mystery.

Thus, one of the important aspects of meteoritics is the study of the trajectories of meteor bodies under various conditions of entry into the Earth's atmosphere, which is the purpose of this chapter. Section 2.2 presents the basic equations for modeling the movement of large meteor bodies in the Earth's atmosphere. Section 2.3 presents the results of numerical calculations of the trajectories of meteor bodies at different angles of their entry into the atmosphere. Conclusions are presented in Sect. 2.4.

2.2 Basic Equations

To identify the main effects that accompany the movement of a large body in the atmosphere, we will study the body trajectory along which it moves under the influence of gravity and aerodynamic forces. In this case, the body mass will be assumed to be constant, meaning the mass loss caused by ablation will be considered insignificant, which is possible for large and durable meteoroids. In this case, changes in the speed of the meteoroid V and the angle of inclination of the velocity vector to the horizon θ are described by Eqs. 2.1–2.4 of the physical theory of meteors [4].

$$M\frac{\mathrm{d}V}{\mathrm{d}t} = \mathrm{Mg}\sin\theta - C_{\mathrm{D}}S\frac{\rho V^2}{2} \tag{2.1}$$

$$\mathrm{MV}\frac{\mathrm{d}\theta}{\mathrm{d}t} = \mathrm{Mg}\cos\theta - \frac{\mathrm{MV}^2\cos\theta}{R_{\mathrm{E}}+z} - C_N S\frac{\rho V^2}{2} \tag{2.2}$$

$$\frac{\mathrm{d}z}{\mathrm{d}t} = -V\sin\theta \tag{2.3}$$

$$\frac{\mathrm{d}L}{\mathrm{d}t} = V\cos\theta \tag{2.4}$$

Here C_{D}, C_N are the coefficients of drag and lift, respectively, S is the area of the body midsection, M is the mass of meteoroid, R_E is the Earth's radius, z is the altitude of the meteoric body above the Earth's surface, L, t are the range and time of the flight, respectively. The change in air density with height z is determined by the formula:

$$\rho = \rho_0\exp(-z/h),$$

where ρ_0 is the atmospheric density with $z = 0$, h is the characteristic scale of altitude. In the Earth's atmosphere, for heights $z < 120$ km, the average value of $h = 7$ km. To solve the system of Eqs. 2.1–2.4, initial conditions are set for $t = 0 : V = V_e, \theta = \theta_e, L = 0, z_e = 100$ km.

We transform Eqs. 2.1–2.2 as follows:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = g\sin\theta - \frac{\rho V^2}{2\lambda}, \tag{2.5}$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \left(\frac{g}{V} - \frac{V}{R_{\mathrm{E}} + z}\right)\cos\theta - K\frac{\rho V}{2\lambda}. \tag{2.6}$$

Equations 2.5–2.6 contain two aerodynamic coefficients: the ballistic coefficient $\lambda = M/C_{\mathrm{D}}S$ and the aerodynamic quality $K = C_N/C_{\mathrm{D}}$. Moreover, the coefficient K for meteor bodies cannot exactly be equal to zero due to the imperfection of their shape, and its value for bodies of irregular geometric shape at hypersonic speeds can be more than 0.1 [5]. When estimating the ballistic coefficient λ for large meteor bodies with a mass of about 10^6 t at a density of 3 g/cm^3, it was found that it can reach $\lambda = 10^5$ kg/m^2. As a result, at high altitudes, the terms in Eqs. 2.5–2.6 representing the aerodynamic forces will be small, meaning that the atmosphere in this case has little effect on the movement of the body. This is the peculiarity of the movement of large meteor bodies in the atmosphere: the ability to penetrate the atmosphere.

2.3 Results of the Calculations

Using the system of Eqs. 2.1–2.4, calculations were made for a stony meteor body with a density $\rho_b = 3$ g/sm^3 and mass $M = 1 \times 10^6$t, entering the Earth's atmosphere at a speed of 30 km/s (these parameters presumably correspond to the Tunguska meteoroid) at different initial angles of entry of the body into the atmosphere. It is assumed that the coefficient of drag is equal to $C_D = 1$, and the value of the ballistic coefficient is $\lambda \approx 1.7 \times 10^5$ kg/m^2. Figure 2.1 shows the changes in the angle of inclination of the trajectory θ depending on the flight time for different initial angles of entry of the body into the atmosphere θ_e without taking into account the fragmentation of the considered body and assuming zero lift ($K = 0$).

It can be seen that the initial angle of entry into the atmosphere has a strong influence on the trajectory and flight time of the body. When $\theta_e \leq 9°$ the angle of the trajectory changes sign over time, and the trajectory becomes ascending. For the angle $\theta_e = 9°$ "ascent" begins on the 40th s of the flight, $\theta_e = 7°$ and $\theta_e = 5°$ the trajectory becomes ascending on the 30th s and the 20th s, respectively.

Data in Fig. 2.2 show how the height of the asteroid's flight changes depending on the flight time for different angles of its entry into the atmosphere. From the results shown, it can be seen that when $\theta_e > 9°$ the meteorite will fall to the Earth, and when $\theta_e \leq 9°$, starting from a certain height, its trajectory becomes ascending.

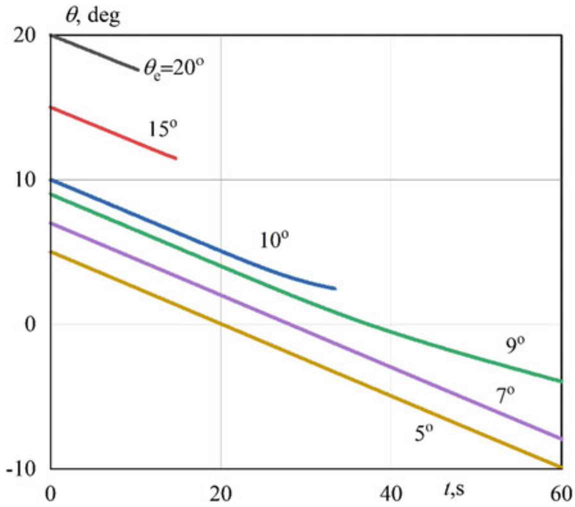

Fig. 2.1 The dependence of the trajectory angle θ on the flight time t of the meteoroid at different angles of entry θ_e into the atmosphere

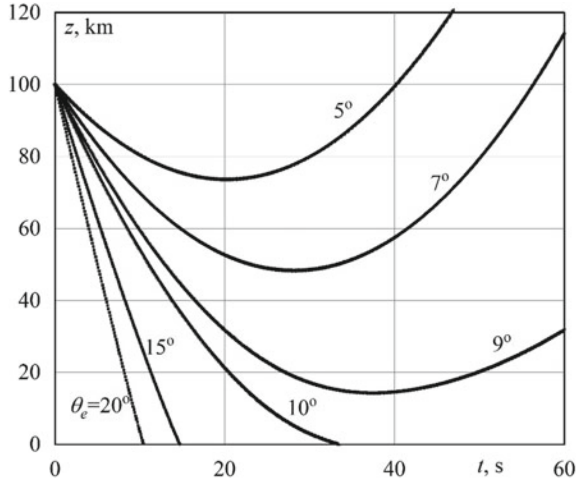

Fig. 2.2 The dependence of the flight altitude z on the flight time t at different angles of entry θ_e into the atmosphere

Figure 2.3 demonstrates how the body is decelerated down in the atmosphere at different angles of entry for a considered meteoroid. It can be seen that at the entry angles of 7° and 9°, the body does not reach the dense layers of the atmosphere, and either weakly slows down or does not lose speed at all.

It is interesting to study the movement of asteroids with the angles of entry into the atmosphere located in the interval $7° \leq \theta_e \leq 10°$. At the angle $\theta_e = 10°$ due to the shortness of the passage in the dense layers of the atmosphere, the meteoroid does not have time to decelerate down significantly and falls to the Earth's surface at the 34th s with a huge velocity of 16 km/s. This leads to an explosion and an almost instantaneous transition of kinetic energy of the meteoroid to mechanical and

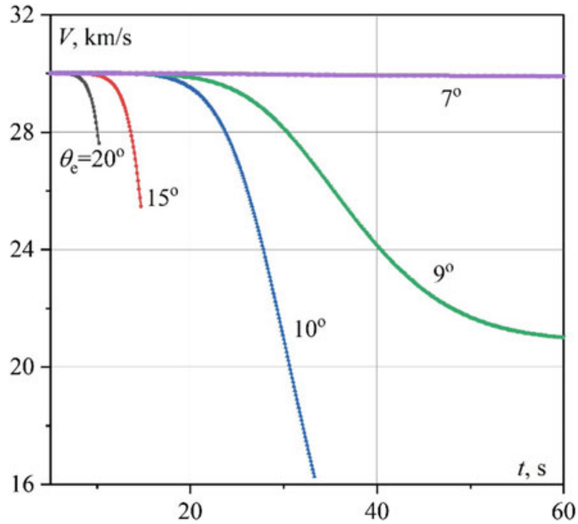

Fig. 2.3 The changing the speed of a meteor body depending on the flight time t for different entry angles θ_e

partially to thermal energy of the rocks surrounding the contact area of the surface, leading to their deformation and the formation of a crater of the funnel elongated in the direction of the fall [6] since this collision with the Earth occurs at an angle $\theta_e = 2.5°$ (see curve 10° in Fig. 2.1).

At the angle $\theta_e = 9°$, the celestial body penetrates only into the stratosphere and moves in it not even in a continuous, but in a transient flow regime, and during this time it loses a little less than a third of its initial velocity: $V = 21\,\text{km/s}$ when $t = 60\,\text{s}$. At the angle $\theta_e = 7°$, moment of time $t = 60\,\text{s}$, the body practically does not reach the dense layers of the atmosphere and almost does not lose velocity at all. At the values of velocities that are observed in Fig. 2.3, a rebound of a celestial body from the dense layers of the atmosphere can occur, like the rebound of a stone from the surface of water, and the meteoroid can fly into outer space.

Obviously, for a range of entry angles $7° \leq \theta_e \leq 10°$ can find a trajectory which is "soft landing", when the body during a long movement in the troposphere is strongly decelerated and at the same time the final part of its trajectory will be almost parallel to the surface. This fall leads to two possible consequences. If the body does not have time to slow down very much, then at a small angle θ_e, a long crater is formed in the direction of the fall, but shallow in depth [6]. As a result of such a meteorite fragment falling is the longest crater in Argentina, Rio Cuarto, which stretches 4.5 km in length, has a width of 1.1 km, and depth of only 7–8 m [7]. If the compacted mass of gas under the meteoroid is large enough, then the speed of its movement can fall significantly, and the impact speed will be close to zero, and such a meteorite will land as if on an air cushion. An example of such a landing is the famous Hoba meteorite (60*t*) in South Africa, which did not leave any noticeable traces when it fell on the surface [8].

The flight range of the meteoroid L for these entry angles is shown in Table 2.1 for flight paths, the range is calculated along the surface of the planet from the projection of the body's entry point into the atmosphere to the projection of its exit point at altitude $z = 100$ km, for the rest trajectories it is calculated from the projection of the body's entry point into the atmosphere to the point of falling off the body.

If the velocity of entry of a meteor body into the Earth's atmosphere is significantly lower than in the cases of data in Figs. 2.1, 2.2 and 2.3 ($V_e = 30$ km/s), then even a small entry angles it can reach the dense layers of the atmosphere, slow down to a speed less than the 2nd space velocity and eventually fall to the Earth. The parameters calculating such the movement of a body with mass $M = 1 \times 10^6$ t and angle of entry into the atmosphere $\theta_e = 7°$ at the initial velocity $V_e = 12$ km/s are shown in Figs. 2.4 and 2.5. From data in Fig. 2.4a, one can see how the angle of inclination of the trajectory decreases over time, and at some point its value becomes negative, but then again there is an increase in the angle of inclination of the trajectory to positive values and the trajectory of the meteoroid crosses the Earth's surface. The velocity of the body near the surface decreases to 4 km/s (Fig. 2.4b).

Table. 2.1 The flight range L of the meteoroid depending on the angle of entry θ_e

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

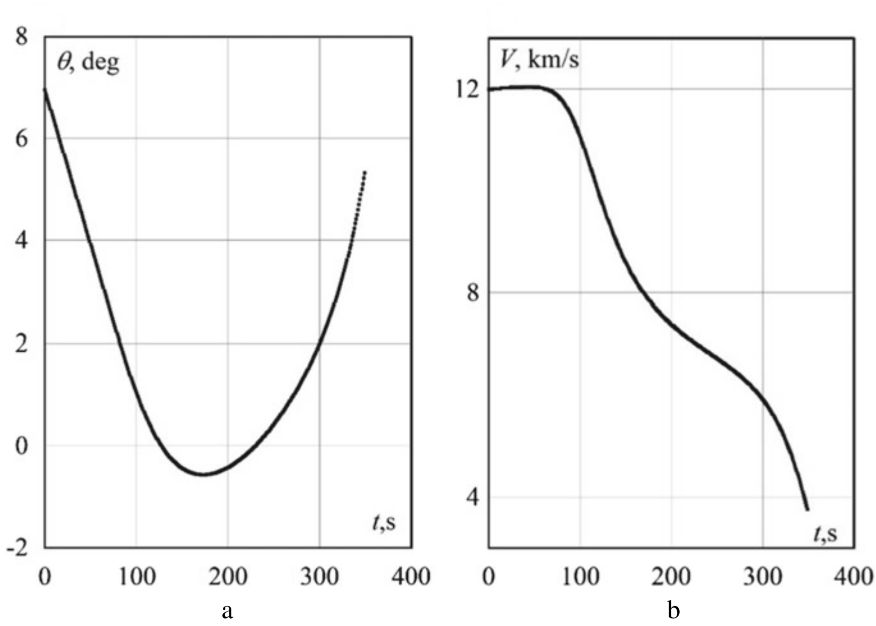

Fig. 2.4 The dependence of: **a** the trajectory angle, **b** velocity V of a meteor body on the flight time t for a body with mass $M = 1 \times 10^6$ t at $V_e = 12$ km/s and $\theta_e = 7°$

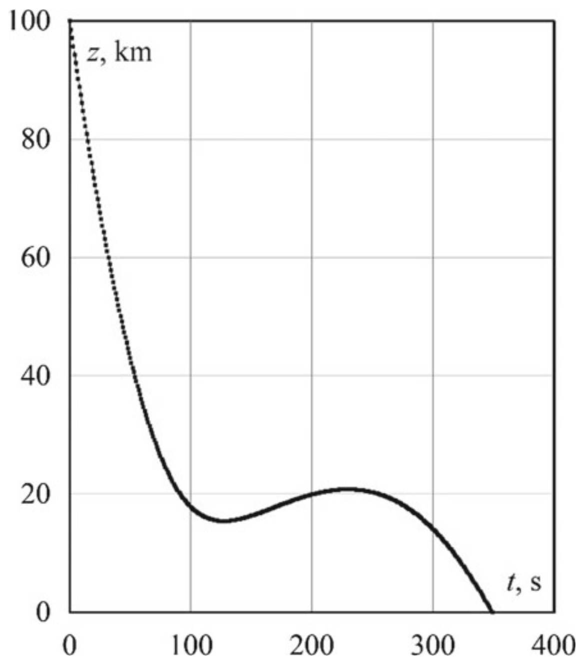

Fig. 2.5 The dependence of the flight altitude on the flight time t for the body mass $M = 1 \times 10^6$ t at $V_e = 12$ km/s and $\theta_e = 7°$

Data in Fig. 2.5 show how the flight height z of such a body changes depending on the flight time t. From these data, one can see the moments of time when the trajectory of the body becomes ascending, and when the stage of falling of the body occurs again. The value of the flight range in this case is $L \approx 3000$ km.

It should be noted that the data presented in Figs. 2.1, 2.2, 2.3, 2.4 and 2.5 are obtained at a zero value of the coefficient of aerodynamic quality: $K = 0$.

Figure 2.6 shows the calculation results of the dependence of the flight altitude z on the flight time t for the angle of entry of the body $\theta_e = 10°$ at different values of the coefficient K. It can be seen that at this value of the angle of entry into the atmosphere and $K = 0$, the trajectory crosses the Earth's surface; at $K \geq 0.1$ the body no longer crashes into the planet, but ricochets from the lower layers of the atmosphere. Moreover, the height of the ricocheting increases as coefficient K grows. In cases of negative values of the coefficient K, the trajectory curves in the other direction and the body falls to the Earth's surface in less time than in the case of $K = 0$.

In the case of negative values of the parameter K, the trajectory of the body, which $K = 0$ could be overflying, is curved in such a way that it falls to the surface of the Earth. This is shown by the curves in Fig. 2.7, which represents the calculation results for the input angle $\theta_e = 9°$ and values $K = 0, -0.1, -0.2$.

Thus, an imperfect geometric shape can have a significant impact on the trajectory of the meteoroid that is, the trajectory can "bend" up or down depending on the sign of the coefficient of aerodynamic quality.

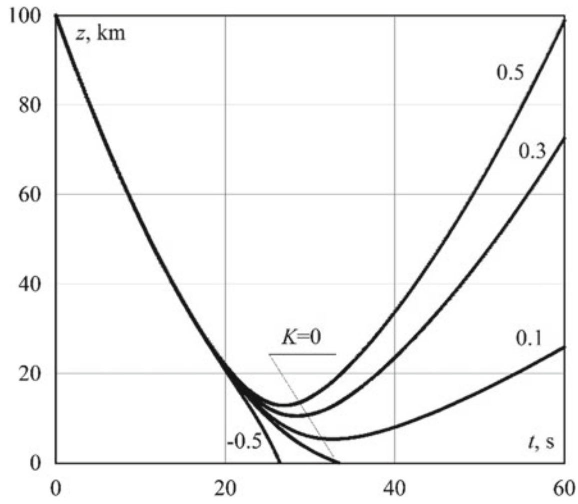

Fig. 2.6 The dependence of the flight altitude z on the flight time t at the angle of entry $\theta_e = 10°$ at different values of the aerodynamic quality coefficient K of the meteoroid

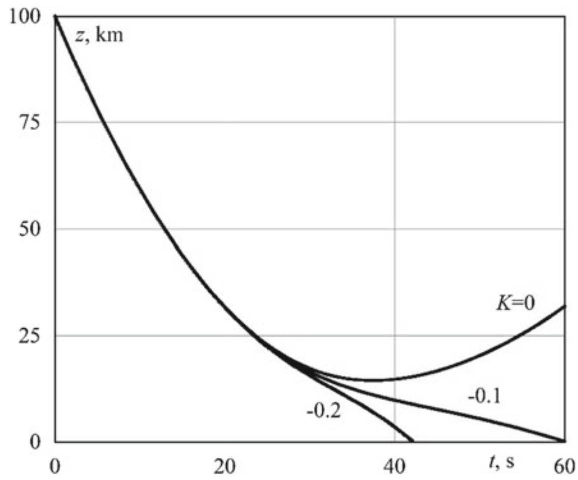

Fig. 2.7 The dependence of the flight altitude z on the flight time t at the angle of entry $\theta_e = 9°$ at different values of the aerodynamic quality coefficient K of the meteoroid

Let's consider the effect of its ballistic coefficient on the trajectory of a body. Suppose that a stone body enters the atmosphere with the velocity $V_e = 30$ km/s, but with a significantly lower mass as the previous one: $M \approx 60$ t, then the value of the ballistic coefficient will be $\lambda \approx 10^4$ kg/m^2.

Data in Fig. 2.8 show how the angle of the trajectory of the body changes depending on the flight time with two values of the ballistic coefficient at the angle of entry into the atmosphere $\theta_e = 9°$. It can be seen that for a body of lower mass ($\lambda \approx 10^4$ kg/m^2), the value of this angle is always positive and increases depending on the flight time (curve 1), whereas for a larger body with a higher value of the

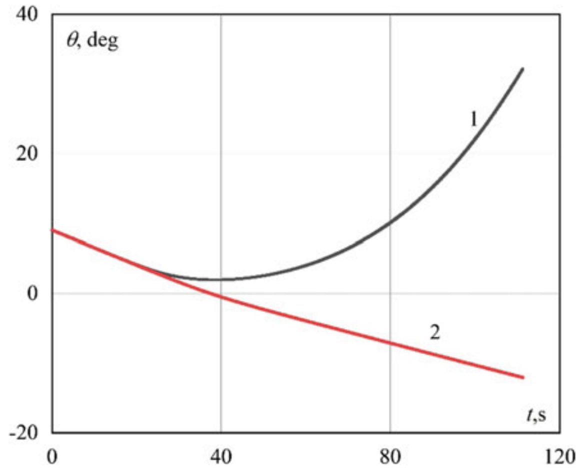

Fig. 2.8 The dependence of the trajectory angle θ on the flight time t of the meteoroid at different values of the ballistic coefficient λ: curve 1—$\lambda \approx 10^4$ kg/m^2, curve 2—$\lambda \approx 1.7 \times 10^5$ kg/m^2

ballistic coefficient ($\lambda \approx 1.7 \times 10^5$ kg/m^2), the value of angle changes sign, that is, trajectory of a body becomes ascending (curve 2).

As the results of the calculation show at $\lambda \approx 10^4$ kg/m^2, the trajectory becomes ascending, and the body acquires the ability to rebound from the atmosphere if the angle of entry into the atmosphere $\theta_e \leq 8°$, as shown by the curves in Fig. 2.9. These curves represent the dependence of the change in the height of the meteoroid flight on time for different angles of entry of the body into the atmosphere. It is seen that a decrease in the coefficient λ leads to a decrease in the critical angle of entry of the body into the atmosphere, below which flyby paths are possible.

The results obtained allow us to explain some of the effects of the Tunguska phenomenon in 1908. If the Tunguska meteoroid invaded the atmosphere at a small

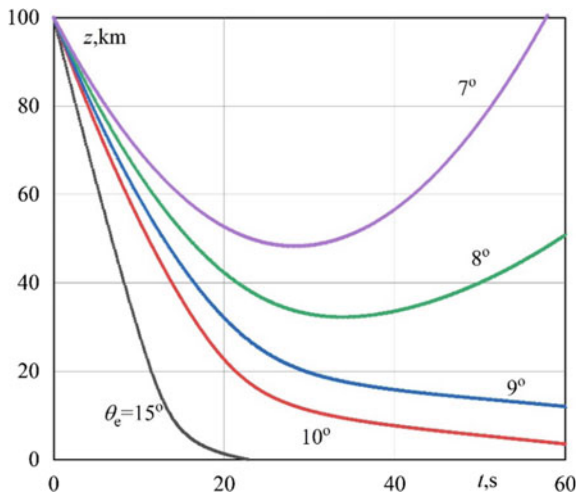

Fig. 2.9 The dependence of the flight altitude z on the flight time t for a body with a mass of 60t and the ballistic coefficient $\lambda \approx 10^4$ kg/m^2 for different angles of entry θ_e into the atmosphere

angle to the horizon ($\theta_e < 9°$), it could be a flyby. This did not exclude its fragmentation with explosions of some of its fragments in the atmosphere, leading to the collapse of the forest, but the main part of sufficiently large fragments could either fall far from the epicenter of the explosion or go into outer space. This assumption is also confirmed by the estimates given in [9]. The hypothesis we have considered allows us to explain the results of studying the proposed fall site of the Tunguska body by many expeditions: the absence of a crater and any material remnants of the meteoritic substance of this body. The results also show that the implementation of flight paths of meteoroids depends on a number of defining parameters of the phenomenon in the aggregate: speed, angle of entry of the body into the atmosphere, ballistic coefficient, and coefficient of aerodynamic quality. In addition, it is also important to take into account the fragmentation and destruction of the meteoroid under the influence of power and heat loads.

2.4 Conclusions

We simulate numerically the flight of large bodies in the Earth's atmosphere. Based on the model of a single body (no fragmentation), we determine the kinematic and physical characteristics necessary for a meteoroid to ascend in the atmosphere after its initial descend. We find that the key parameter for the possibility of such ascend is the angle of entry into the atmosphere. We compute the critical angles for a range of control parameters, i.e. the ballistic coefficient and the lift-to-drag ratio. Our results explain certain effects of the Tunguska event that took place in 1908.

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