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Classification of the Consequences for Collisions of Cosmic Bodies with the Earth

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Abstract

This study is devoted to description of the possible results that might accompany collisions of natural cosmic bodies with both the Earth's atmosphere and the Earth's surface. The methodology of the classification is based on the analytical solution of differential equations of meteor physics. These equations characterize the body's trajectory in the atmosphere, namely, the dependences of the body's velocity and mass on the flight altitude. The solution depends on two dimensionless parameters defining the drag rate and altitude, and the role of the meteoroid's mass loss when it moves in the atmosphere. The action of the collisions on the planet's surface essentially depends on values of these two parameters. Additionally we formulate recommendations for further studies of the important problem related to the interaction of cosmic bodies with planet atmospheres [1].

1. Introduction

When meteoroid enters the Earth's atmosphere, its ablation rate depends on the meteoroid's velocity while deceleration is determined by its mass. Therefore the mass loss and the drag equations for a meteoroid assumed to be solved simultaneously:

$$M\frac{dV}{dt} = -\frac{1}{2}c_d\rho_a V^2 S \qquad (1)$$

$$H^*\frac{dM}{dt} = -\frac{1}{2}c_h\rho_a V^3 S \qquad (2)$$

Here M, V, and S are the mass, velocity, and the cross section area of the body, respectively; c_d is the drag coefficient; ρ_a is the atmospheric density; H^* is the effective destruction enthalpy and c_h is the heat-transfer coefficient.

The system of Eqs. 1 and 2 has a known analytical solution under certain assumptions (see e.g. [2]). This solution is based on global, rather than local, description of the motion. Let h be the altitude above the surface and γ the local angle between the trajectory and the horizon. Then, the geometric relation:

$$dh = -V\sin\gamma dt \qquad (3)$$

along the trajectory is used to introduce the new variable h instead of t.

For an isothermal atmosphere the relation between altitude and velocity then appears as a first integral of the differential Eqs. 1 and 2:

$$y = \ln 2\alpha + \beta - \ln(\overline{E}i(\beta) - \overline{E}i(\beta v^2)) \qquad (4)$$

Where the dimensionless quantities are introduced as follows:

$$v = V/V_e,\; y = h/h_0 \qquad (5)$$

$$\alpha = \frac{1}{2}c_d\frac{\rho_0 h_0 S_e}{M_e\sin\gamma},\quad \beta = (1-\mu)\frac{c_h V_e^2}{2c_d H^*} \qquad (6)$$

Here the atmospheric scale height h_0 and the density ρ_0 near the surface are used as the altitude and density scales respectively, μ is the shape change coefficient, and the subscript e refers to the values at the entry into the Earth's atmosphere. The solution (4) is valid under natural conditions $v > 0$, $y > 0$ and takes into account the dependence of the shape of the luminous trajectory segment on the ballistic coefficient α and mass loss parameter β, which characterize the meteoroid deceleration and ablation respectively.

2. Basic classification and results

Below, we propose several examples of collisions of cosmic bodies with the Earth and their consequences. These examples are supplemented by brief analysis of actual events.

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 (Fig. 1).

2. The range $\alpha < 1$, $\beta < 1$: fracture of the meteor body in the atmosphere and deposition of a cloud of fragments onto the Earth's surface take place with the formation of a crater and meteorite fields. Modern mathematical models describing the motion of the fragment 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 (1947, Russia).

3. The range $\alpha \sim 1$, $\beta \sim 1$. 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 luminous segment of atmospheric trajectory were observed, meteorite fragments being also found in a number of cases. Among them, there are famous bolides Neuschwanstein (2002, Germany), Innisfree (1977, Canada) and Lost City (1970, United States). They are relatively small meteoroids, thus the total mass of meteorites collected on the Earth's surface is on the order of 10 kg [3]. The absence of craters is explained by the same reason. The characteristic feature of the collected meteorites is the presence of ablation traces on their surface.

4. The range $\alpha < 1$, $\beta >> 1$: 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-vapour jet onto the Earth's surface. Descending in the atmosphere, the gas volume expands [4]. 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 action region exceeds the characteristic size of the original meteoroid by several orders of magnitude. The well-known Tunguska event (June 30, 1908) in Siberia serves as a real example.

The found distribution of parameters α and β is given on the Fig. 2. The curve shows the analytically derived margin between the meteorite region and fully ablated fireballs.

Figure 1: Barringer crater, Arizona, United States.

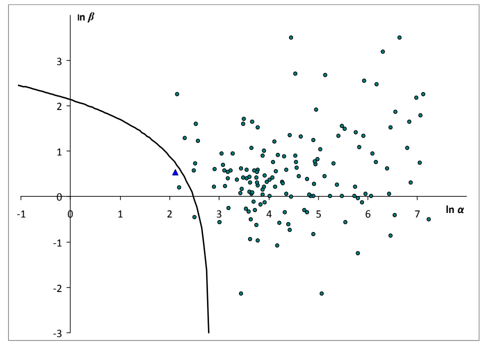

Figure 2: Distribution of parameters α and β for fireballs registered by Meteorite Observation and Recovery Project in Canada. ▲ corresponds to the unique meteorite found on the ground in the frame of the project (Innisfree). The curve shows margin between the region with expected meteorites on the ground and fully ablated fireballs.

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