HEAT TRANSFER, MASS ENTRAINMENT, AND LUMINOSITY OF BOLIDES

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The problem of the motion of bodies in the earth's atmosphere is solved with the use of radiative gas dynamics equations. The effective enthalpy of disintegration is determined from the condition of the best approximation of the predicted trajectory to that observed.

The problem of studying the entry of meteoric bodies into the Earth's atmosphere is of interest from several standpoints. Primarily, the observations of meteors provide certain information about the state of the upper atmosphere. Furthermore, correct interpretation of meteoric phenomena may furnish information about the physicomechanical properties of bodies in the circumterrestrial cosmos. Finally, comprehensive investigation of the interaction of the small bodies of the solar system with the atmosphere supplies the starting information for realistic evaluation of the so-called asteroidal hazard. In other words, the study of meteors and bolides is one of the ways of determining the role of collisions with cosmic bodies in the formation of the geological and biological history of the Earth. The results should be taken into consideration when predicting all kinds of processes capable of affecting the fate of civilization.

In 1959 the Czechoslovak Meteor Patrol took photographs of the trajectory of a great bolide. After the place of its fall had been localized by extrapolating the luminous portion of the trajectory to the earth, several fragments of the Prsibram meteorite with the total mass \( M_k = 5.8 \) kg were discovered. In subsequent years, a number of countries arrived at the decision to set up bolide networks for continuous observation and photorecording of bolides. The European bolide network has been active since 1964. The Prairie network in the USA functioned from 1964 to 1975. At the beginning of 1970 four fragments of the Lost-City meteorite with \( M_k = 17.1 \) kg were found after photographs of its trajectory had been taken. The Canadian network (1971-1985) also discovered one meteorite (Innisfree, 1977, \( M_k = 4.6 \) kg). Simultaneously, vast photographic material has been accumulated, a portion of which is published in [1-3]. It is natural to try to use these data for determining the physicomechanical properties of meteoroids with account for the well-known laws governing the motion of bodies in the atmosphere. The most important parameters are the entry mass of the meteoric body, its density, and its specific heat of disintegration.

In the works on meteors [4, 5] the opinion is held according to which the vapors of the meteoric body are mainly responsible for the meteor luminosity. Extensive use is made of the photometric formula

\[
I = -\tau \frac{V^2}{2} \frac{dM}{dt},
\]

which relates the rate of mass entrainment \( dM/dt \) to the luminosity \( I \) through the luminosity coefficient \( \tau \); here \( V \) is the meteor velocity. Formula (1) is used for determining the entry mass of the meteoroid by integrating the observed luminosity function \( I(t) \) along the trajectory. The thus obtained value for the photometric mass \( M_{ph} \) is much in excess of the entry mass \( M_e \) determined from the body drag. Also used is a more general formula [6]

\[
I = -\tau \frac{dE}{dt}, \quad \frac{dE}{dt} = \frac{V^2}{2} \frac{dM}{dt} + MV \frac{dV}{dt}.
\]
Investigations of trajectories show that neglecting in Eq. (2) the contribution made by the drag \( MV \frac{dV}{dt} \) in the case of bolides introduces large errors. In other words, the theory and the results of measurements of the luminosity coefficient \( \tau \) which were obtained for micrometeorites cannot be extended to bolides.

Formulas (1) and (2) do not take into account the nature of radiation produced by meteoric bodies when moving in the atmosphere.

One of the pioneers in the application of achievements in physicochemical gas dynamics to the analysis of meteoric phenomena was Academician G. I. Petrov [7]. The gas-dynamic approach to the determination of heat transfer, mass entrainment, and luminosity of bolides was conceived and developed in works [8-10].

The flow of the atmosphere gas near a meteoric body is modeled by a uniform flow around a smooth blunt body at a high supersonic velocity. The main regularities of such a flow are rather well known. In [11] these regularities were used to develop the algorithm for calculating the trajectories of bodies in the atmospheres of planets.

The equations of body motion and mass entrainment, neglecting the body weight and lift, have the form

\[
\frac{dV}{dt} = -\frac{1}{2} C_d \rho V^2 S, \quad \frac{dH}{dt} = -V \sin \gamma, \quad H^* \frac{dM}{dt} = -\frac{1}{2} C_h \rho V^2 S. \tag{3}
\]

Here \( H \) is the height; \( \gamma \) is the angle between the trajectory and the horizon; \( C_d, C_h \) are the coefficients of resistance and heat transfer; \( S \) the midsection area of the body; \( H^* \) the effective enthalpy of disintegration.

For the isothermal atmosphere \( \rho = \rho_0 \exp(-H/h_0) \), and taking into account the assumption that \( S/S_e = (M/M_e)^\mu (\mu = \text{const}) \) [12] we have the familiar analytical solution of Eqs. (3) for the trajectory

\[
m = \exp \left[ -\frac{\beta}{1-\mu} (1 - \nu^2) \right],
\]

\[
y = \ln \alpha + \beta - \ln \Delta/2, \quad \Delta = \bar{E}_i(\beta) - \bar{E}_i(\beta \nu^2),
\]

which involves two parameters being constant along the trajectory: the ballistic coefficient \( \alpha = 1/2 C_d (\rho_0 h_0 S_e/M_e \sin \gamma) \) and the mass entrainment parameter \( \beta = (1-\mu) (C_h V_e^2/2C_d H^*) \). Solution (4) is written in dimensionless variables: \( m = M/M_e, \nu = V/V_e, y = H/h_0 \), the subscript \( e \) means the entry conditions.

Estimations and rapid calculations are found to be difficult because of the presence of the integral exponent \( \bar{E}_i(x) \) in Eqs. (4). A. L. Kulakov has shown that the second formula in system (4) can be rather accurately replaced by the following expression

\[
y = \ln \alpha - \ln (-\ln \nu) + 0,83\beta (1 - \nu). \tag{5}
\]

The real trajectories with variable aerodynamic coefficients \( C_d \) and \( C_h \) and varying shape of the body are obtained by numerical integration of Eqs. (3). Examples of calculations are given in [11].