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# 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

$$I = -\tau \frac{V^2}{2} \frac{dM}{dt}, \tag{1}$$

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]

$$I = -\tau \frac{dE}{dt}, \quad \frac{dE}{dt} = \frac{V^2}{2} \frac{dM}{dt} + MV \frac{dV}{dt}. \tag{2}$$

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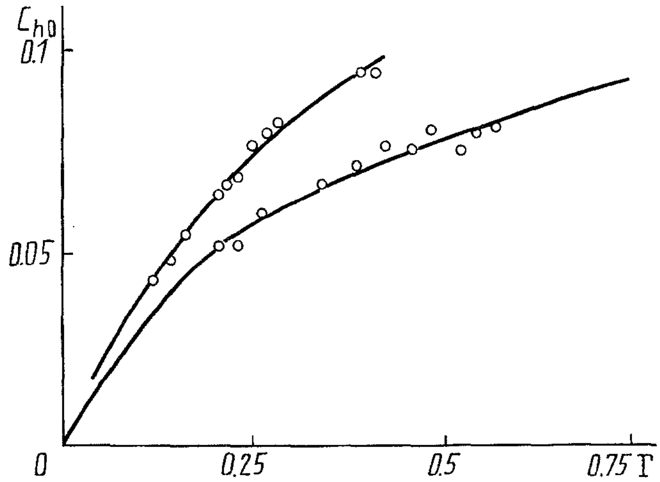


Fig. 1. Radiative heat transfer coefficient vs the fluorescence parameter.

Investigations of trajectories show that neglecting in Eq. (2) the contribution made by the drag MVdV/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

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

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 $S/S_e = (M/M_e)^{\mu}$ ($\mu$ = const) [12] we have the familiar analytical solution of Eqs. (3) for the trajectory

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

$$y = \ln\alpha + \beta - \ln\Delta/2, \quad \Delta = \overline{E}_i(\beta) - \overline{E}_i(\beta v^2), \tag{4}$$

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

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

$$y = \ln\alpha - \ln(-\ln v) + 0{,}83\beta(1-v). \tag{5}$$

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].

Correct determination of the heat transfer coefficients $C_h$ plays an important role. Parametric calculations of the hypersonic gas mixture flow past the upstream portions of blunt bodies in the presence of radiative heat transfer [13, 14] made it possible to establish a simple dependence of the coefficient $C_{h0}$ at the stagnation point on some dimensionless numbers:

$$C_{h_0} = a\Gamma^b, \tag{6}$$

where $\Gamma = 2q_{ad}/0.5\rho V^3$ and $q_{ad}$ is the radiative flux from the axial part of the adiabatic shock layer, i.e., that calculated without account for radiative cooling. The numbers a and b in Eq. (6) have the following values:

$$\begin{aligned} &a=0{,}111,\ b=0{,}53 \text{ — air},\\ &a=0{,}186,\quad b=0{,}69 \text{ — mixture } H_2+\mathrm{He}. \end{aligned} \tag{7}$$

Equations (6) and (7) (solid curves) and the approximated results of numerical calculations (points) are presented in Fig. 1.

The description of the meteoric body mass entrainment within the framework of the third equation of system (3) presupposes the knowledge of the quantity $H^*$. The value of $H^*$ depends on the physical process determining the entrainment of mass. For meteoroids the following processes are typical: quasi-continuous crushing, melting with the formation of liquid film, and evaporation. Information about the prevailing process can be gained from the rate of mass entrainment, which in turn exerts an influence on the form of the trajectory being observed.

Below a method is presented for determining the meteoric body entry mass $M_e$ and the effective disintegration enthalpy $H^*$. The method consists in the determination of the parameters $\alpha$ and $\beta$ from the condition of the best approximation of Eq. (5) to the trajectory observed. The calculations were performed for the bolides of the Prairie network [2].

Two schemes of the method are considered. In the first case the following sum is made up:

$$Q_1(\alpha, \beta) = \sum_{i=1}^{n} [y_i(v_{Hi}, \alpha, \beta) - y_{Hi}]^2. \tag{8}$$

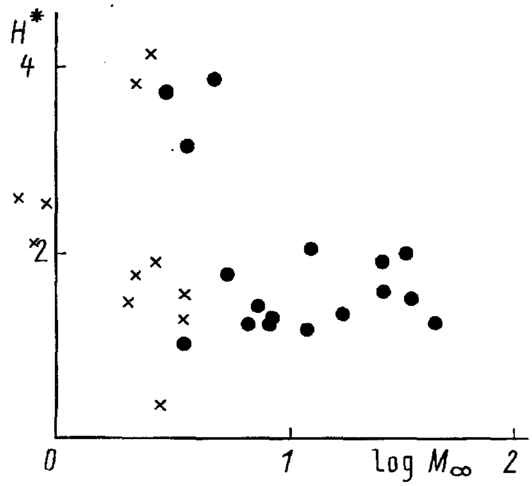
Here $y_{Hi}$ and $v_{Hi}$ are the height and velocity of flight taken from the observation tables of [2]. The minimum of function (8) is realized at the following values of $\alpha$ and $\beta$:

$$\begin{gathered} \alpha = \exp\left\{\frac{1}{n}\sum_{i=1}^{n}[-0{,}83\beta(1-v_{Hi}) + \ln(-\ln v_{Hi}) + y_{Hi}]\right\},\\ \beta = \frac{\sum_{i=1}^{n}\left\{\ln(-\ln v_{Hi}) + y_{Hi} - \sum_{j=1}^{n}[\ln(-\ln v_{Hj}) + y_{Hj}]\right\} v_{Hi}}{0{,}83\sum_{i=1}^{n}\left[\frac{1}{n}\sum_{j=1}^{n}(1-v_{Hj}) - (1-v_{Hi})\right] v_{Hi}}. \end{gathered} \tag{9}$$

The values of $\alpha$ and $\beta$ in Eqs. (9) change substantially when the initial points of the trajectory are taken into account where there is still no perceptible deceleration of the meteoroid. These points should not be taken into account in Eq. (8). It is difficult to formulate the correct criterion for selecting the points, and therefore the result depends on preliminary estimates. The second scheme of the method has been adopted as the basic one where the minimum of the sum is determined:

$$Q_2(\alpha, \beta) = \sum_{i=1}^{n} [v_i(y_{Hi}, \alpha, \beta) - v_{Hi}]^2, \tag{10}$$

and the values of $v_i(y_{Hi}, \alpha, \beta)$ are calculated with the aid of the function reciprocal to (5). The unknown minimum is realized at $\alpha$ and $\beta$ determined from the system of equations



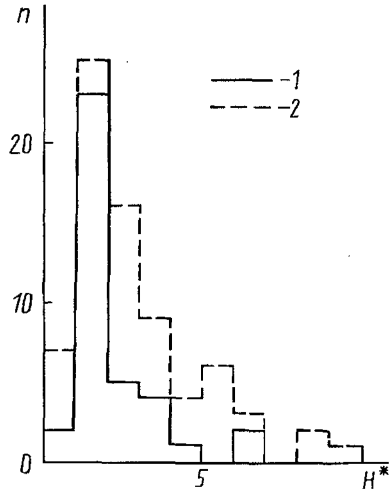




Fig. 2. The $M_e$-$H^*$ diagram for large bolides. $H^*$, $10^3$ J/g; log $M_\infty$, kg.

Fig. 3. Distribution of the number of bolides having the value of $H^*$ in the given range: 1) $M_e > 1$ kg; 2) $M_e < 1$ kg.

$$y_{Hi} = \ln\alpha - \ln(-\ln v_i) + 0{,}83\beta(1 - v_i),$$
$$\sum_{i=1}^{n} \frac{(v_{Hi} - v_i)\, v_i^2 \ln v_i}{1 + 0{,}83\beta v_i \ln v_i} = 0, \quad \sum_{i=1}^{n} \frac{(v_{Hi} - v_i)(v_i \ln v_i)}{1 + 0{,}83\beta v_i \ln v_i} = 0. \tag{11}$$

System (11) contains n + 2 unknown values of $\alpha, \beta, v_i$ ($i = 1, \ldots, n$) and is solved by the method of iterations in which the values in (9) are selected as the initial approximation for $\alpha$ and $\beta$.

Upon finding $\alpha$ and $\beta$, we determine the values of $M_e$ and $H^*$. The ratio $S_e/M_e$ involved in $\alpha$ can be conveniently represented in terms of the form factor $A_e = S_e/\Omega_e^{2/3}$:

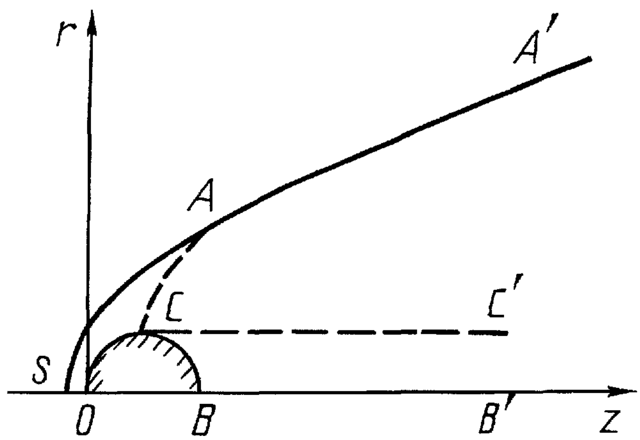
$$\frac{S_e}{M_e} = \frac{A_e}{\rho_T^{2/3} M_e^{1/3}}. \tag{12}$$

Here $\rho_T$ is the density of the meteoroid material; $\Omega$ is the body volume. With account for (12), the expressions for $\alpha$ and $\beta$ involve 11 parameters including the unknown $M_e$ and $H^*$ values. Of these, $\rho_0$ and $h_0$ are known parameters of the atmosphere, whereas $\gamma$ and $V_e$ are determined from trajectory measurements. The five parameters $C_d$, $C_h$, $\rho_T$, $A_e$, and $\mu$ can be found from physical theories or special hypotheses. Here it is assumed that $C_d^0=1$, $C_h^0=0.02$, $\rho_T^0=3.73$ g/cm$^3$ (the density of the Lost-City meteorite), $A_e^0=1.21$ (sphere), and $\mu^0 = 0$ (the absence of rotation). Below, simple formulas are suggested for converting the unknown parameters $M_e$ and $H^*$, if we take other values for the latter five parameters:

$$\frac{M_e}{M_e^0} = \left(\frac{C_d A_e}{C_d^0 A_e^0}\right)^3 \left(\frac{\rho_T^0}{\rho_T}\right)^2, \quad \frac{H^*}{H^0} = \frac{1-\mu}{1-\mu^0} \frac{C_h}{C_h^0} \frac{C_d^0}{C_d}. \tag{13}$$

In what follows, the numerical values of the unknown parameters $M_e^0$ and $H^{*0}$ are discussed.

Calculations were performed for 110 versions from the tables of [2]. The largest objects were selected and, moreover, we took care that the entry velocity for the calculated versions was not much in excess of 20 km/sec. The results of calculations are presented as a diagram in the coordinates ($M_e$, $H^*$) in Fig. 2, where the versions with $M_{ph} > 50$ kg (dark points) and with $50 > M_{ph} > 10$ kg (crosses) are given; other variants are not presented. The values of $H^*$ for rather large bolides ($M_e > 5$kg) lie within relatively narrow ranges from 1000 to 2000 J/g. The distribution over the values of $H^*$ for all the versions is given in Fig. 3 in the form of a histogram showing the number of bolides that have the value of $H^*$ within the given range equal to the base of the corresponding column. The variance of small bolides over the scale of $H^*$ (dashed line) is much higher than for larger ones.



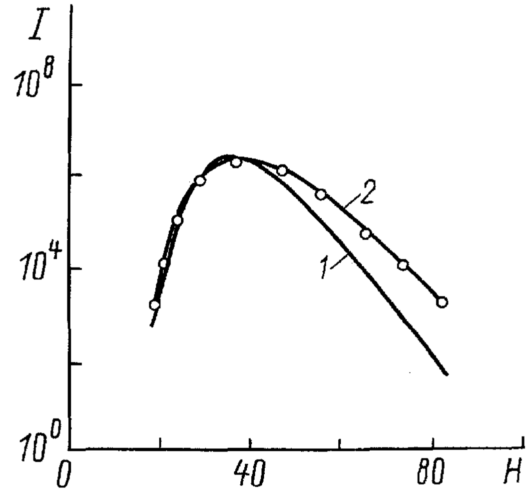




Fig. 4. Schematic of the supersonic flow around a sphere.

Fig. 5. The predicted and natural luminosity of the Lost-City bolide. I, W; H, km.

In the literature the trajectories and luminosity of the Lost-City bolide have been rather comprehensively studied [9, 15, 16]; therefore it is worthwhile to make some comparisons. For this case, formulas (11) gave the values $\alpha = 12.05$ and $\beta = 1.01$. In [15] the ballistic coefficient $\nu$ was calculated directly from the deceleration equation and therefore it varied along the trajectory (Fig. 4 in [15]). The coefficients $\nu$ and $\alpha$ are related by the formula

$$\nu = \frac{1}{2} \frac{\rho_0 h_0}{\alpha \sin\gamma}. \tag{14}$$

Assuming $\sin\gamma = 0.607$, we obtain from (14) that $\nu = 63.138$ g/cm$^2$. This value is very close to the initial value of $\nu$ in Fig. 4 of work [15], where it was equal to about $10^{1.8} = 63.096$. The decrease of $\nu$ shown in this figure is represented in our model by the mass entrainment parameter $\beta$. Over the initial section of the trajectory, for which the comparison was made, the entrainment is insignificant.

The value $M_e = 32$ kg obtained here for the Lost-City bolide is close to the value found earlier in [9]. Just as in our work, the authors of [9] make an assumption about the initial spherical shape, which becomes more and more blunt along the trajectory. On the other hand, the attempts to mate the $M_{ph}$ and $M_e$ values for the Lost-City bolide made in [15] lead to a plane form of the type of a comparatively thin disk ($A = 2$). The coupling between $M_e$ and A is given in the first formula of system (13). Therefore, to be able to finally assess the value of $M_e$ without the assumption on its shape, it is necessary to have additional information.

Let us compare our calculations of $M_e$ with the results of work [16], where data on the light curve are resorted to for determining this value. Evaluation of the characteristic size allows the authors of [16] to determine the range of values of the parameter $\rho_T/C_dA_e$. For the Lost-City bolide it was obtained that $\rho_T/C_dA_e = 1.1 - 2$g/cm$^3$. Since the values of $\rho_T$ and $C_d$ are known rather exactly, hence we may obtain the estimate of the coefficient of the form: $A_e = 1.67 - 2.49$. Using Eq. (13) and assuming that $M_e^0 = 32$ kg, we obtain $M_e = 85$-$280$ kg. This corresponds quite well to the estimates of [16] (80-250 kg) made with predominant use of the light curve.

Within the framework of the gas-dynamic approach, at Moscow University some models were suggested and calculations performed for the luminosity of meteors moving along their trajectories.

The solution of the problem of high-velocity gas flow past bodies with the aim of determining the drag and heating was usually made either in the vicinity of the stagnation point [13] or for the subsonic and transonic shock layer regions [11, 14, 17]. However, to determine the luminosity of a meteor it is necessary to know the gas flow field in the possibly larger region including the body wake. Therefore, a special simplified model of flow around a body was developed which allows one to approximately obtain the real temperature and pressure fields in equilibrium flow around bodies.

The model is depicted in Fig. 4 on the example of flow around a sphere. The wake flow is replaced by an impermeable cylinder with the generatrix $CC'$. The needed temperature and pressure distributions are obtained as follows: 1) in the region OSAC the values of p and T are obtained by solving numerically the problem of equilibrium emitting air flow around a sphere; 2) in the region $A'ACC'$ these values are obtained by calculating the longitudinal flow around the cylinder; 3) in the region C-CBB- the values of p and T are assumed to be constant in the lateral sections and equal to the corresponding values on the generatrix $CC'$. Here CA is the characteristic from the midsection point.

On the basis of the data given in [15], the following formula for coupling the star value with the integral light flow from the far-removed object is adopted [18]:

$$m = -2{,}5 \lg E - 13{,}56. \tag{15}$$

Here E is the illumination of unit area expressed in $erg/cm^2 \cdot sec$.

Assuming that in the optical range of frequencies the emitting volume is optically transparent, we shall write down the expression for the illumination in the following form:

$$E = \frac{4\pi}{L^2} I_w, \quad I_w = \int_{\lambda_1}^{\lambda_2} \int_w \varkappa_\lambda B_\lambda dW d\lambda. \tag{16}$$

Here integration is carried out over the entire emitting volume (the body of rotation of the region $B'BCOSA'A$ in Fig. 4), since blocking of a portion of the volume can be neglected. In the tables of work [2] the values of m are reduced to the standard distance L = 100 km. Expressing the intensity $I_w$ in watts, we obtain the unknown coupling with m:

$$\lg I_w = -0{,}4m + 2{,}86. \tag{17}$$

Numerical integration of Eq. (16) leads to the calculated value of m.

A. I. Vislyi [10] performed systematic calculations of the luminosity $I_w$ in a wide range of the parameters of the flow incident on a sphere and approximated the results by an expression in the form of the entry function

$$I_w = 5{,}84 \cdot 10^{11} R^a (V/10)^b \rho^c, \quad a = 3; \; b = 12{,}62; \; c = 1{,}69. \tag{18}$$

Here $I_w$ is defined in watts, the sphere radius R in meters, the flow velocity V in km/sec and the density of the atmosphere $\rho$ in $kg/m^3$. Formula (18) is applicable within the following ranges: $0.01 \le R \le 1$; $8 \le V \le 18$; $7.4 \cdot 10^{-2} \ge \rho \ge 1.81 \cdot 10^{-5}$ and should replace Eq. (1) in the case of bolides. It deserves refinement for other models of flow differing from equilibrium flow around smooth bodies.

Below, results are given obtained from comparison of the natural light curve of the Lost-City meteorite [2] with data calculated by the above-stated method. The following parameters of meteoric bodies were selected as initial: the radius of the sphere was $R_e = 0.105$ m, its mass was $M_e = 18$ kg. In these calculations, performed earlier than the calculations of $M_e$ and $H^*$ made in this work, it was assumed that the mass is entrained by evaporation and therefore $H^* = 8368$ J/g. The underestimated mass $M_e = 18$ kg (against $M_e = 32$ kg) is explained by the overestimation of $H^*$ (against $H^* = 1997$ J/g). At several points evenly located along the trajectory, a calculation was made for the flow around a body with a varying shape of its upstream portion and for the shock layer luminosity by the above-stated model. The results are shown in Fig. 5, depending on the height of flight (curve 1). Curve 2 shows the results of observations [2].

Comparison of the data reveals qualitative agreement on the other half of the trajectory. Simultaneously, at high altitudes the actual values of luminosity substantially exceed those predicted. Possibly, at high altitudes one should use other flow models. Thus, the estimates show that freezing of the excited states of atoms and ions as well as the degrees of air ionization in the region $A'ACC'$ (see Fig. 4) may lead to a rise in luminosity by a factor of 4 to 6. On the first half of the trajectory quasi-continuous crushing of the meteoroid may play a certain role [19], leading to the additional luminosity of fine particles in the shock layer.

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