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ON THE MECHANISM BEHIND THE FRAGMENTATION OF TINY METEOR BODIES IN THE ATMOSPHERE

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SUMMARY

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It is shown in this work that the various peculiarities of of tiny meteors, revealed by photographic observations and usually explained by the very looseand friable structure of their bodies, can in reality by explained without resorting to that hypothesis.

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The simplest physical theory of meteors [1] gives the following distribution of the force I of light along the meteor path :

$$\frac{I}{I_m} = \frac{9}{4}\frac{\rho}{\rho_m}\left(1 - \frac{1}{3}\frac{\rho}{\rho_m}\right)^2, \qquad (1)$$

where I_m is the maximum light force; ρ, ρ_m are respectively the densities of the atmosphere at the given altitude and at the altitude maximum of the light force. The curve for the force of light (1) agrees well with the observations of meteors, brighter than about the zero stellar magnitude.

Photographic observations with the aid of the Super-Schmidt cameras [2, 3] reveal a series of peculiarities of weak photographic meteors of 0 — +4 stellar magnitude:

a) shortening of wakes (trails) by comparison with (1);

b) rapid accretion of shine near the point of appearance;

c) anomalous braking increase at the end of the trail;

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d) the washing away of the discontinuities in the second half of the trail on photographs obtained with the aid of a shutter.

These peculiarities are usually explained [2, 3] by the very loose or friable structure of meteor bodies, which leads to their fragmentation under the action of aerodynamic pressure. In the present work it is shown that these peculiarities may be explained without resorting to the hypothesis on the unusually friable structure of meteor bodies.

Let us consider the motion of a rotating spherical meteor body in the upper atmosphere. In this case the energy, which is transferred to the meteor body by air molecules colliding with it, is approximately uniformly distributed over its surface. The density of the heat flux through the body surface is

$$\varphi(t) = \frac{1}{8}\Lambda v^3\rho = \frac{1}{8}\Lambda v^3\rho_0 \exp\left(\frac{vt\cos z}{H}\right), \qquad (2)$$

where t is the time; Λ is the heat-transfer coefficient; v is the v elocity of the body; ρ_0 is a constant; z is the zenithal distance of the radiant of the meteor; H is the reduced height of uniform atmosphere.

The heat conductivity equation in spherical coordinates has the form

$$\frac{\partial\tau}{\partial t} - b^2\left(\frac{\partial^2\tau}{\partial r^2} + \frac{2}{r}\frac{\partial\tau}{\partial r}\right) = 0, \quad b^2 = \frac{\lambda}{c\delta}, \qquad (3)$$

where $\tau(r,t)$ is the temperature counted from the initial temperature T_0 of the body; λ is the heat conductivity factor; c is the heat capacity; δ is the density of the body. The boundary conditions are

$$\tau(r, -\infty) = 0, \quad (\partial\tau/\partial r)_{r=0} = 0, \quad \lambda(\partial\tau/\partial r)_{r=r_0} = \varphi(t) \qquad (4)$$

(r_0 being the radius of the body).

At such boundary conditions and provided we neglect the deceleration, the solution of the equation (3) has the form [4]

$$\tau(r, \rho) = \frac{\Lambda r_0 v_0^3\rho}{8\lambda\left[\frac{1}{x_0}\operatorname{ch}\left(\frac{r_0}{x_0}\right) - \frac{1}{r_0}\operatorname{sh}\left(\frac{r_0}{x_0}\right)\right]}\frac{1}{r}\operatorname{sh}\left(\frac{r}{x_0}\right); \quad x_0 = b\sqrt{\frac{H}{v_0\cos z}}. \qquad (5)$$

The latent heat of meteor matter melting is about equal to the energy required for its heating from 0° K to $T_0 \approx 280^{\circ}$ K; this is why in (5), at $T > T_m$ (T_m being the temperature of melting), it is better to count the temperature from 0° K. The temperature of body surface is

$$\tau(r_0, \rho) = \frac{\Lambda r_0 v_0^3}{8\lambda\left[\frac{r_0}{x_0}\operatorname{cth}\left(\frac{r_0}{x_0}\right) - 1\right]}. \quad (6)$$

The rate of matter evaporation in vacuum may be written in the following form:

$$\lg(\Delta M) = -4{,}23 + C_1 + {}^1/_2 \lg\mu - C_2/T - {}^1/_2 \lg T. \quad (7)$$

Here ΔM is the mass of the matter evaporating from the unit of surface in the unit of time; C_1 and C_2 are constants; μ is the molecular weight.

Equating the energy expended on vaporization at temperature given by formula (6), $\varphi(t)$ from "2), (6) and (7), we find the atmosphere density at the height h_H of the beginning of intensive vaporization of the meteor body

$$\rho_H = \frac{8\lambda C_2\left[\frac{r_0}{x_0}\operatorname{cth}\left(\frac{r_0}{x_0}\right) - 1\right]}{\Lambda r_0 v_0^3\left\{-4{,}23 + C_1 + \lg Q + \frac{1}{2}\lg\mu + \lg\frac{r_0}{\lambda} + \lg\left[\frac{r_0}{x_0}\operatorname{cth}\frac{r_0}{x_0} - 1 - \frac{3}{2}\lg T_H\right]\right\}}, \quad (8)$$

where Q is the vaporization energy of 1 g of meteor matter; T_H is the temperature of the beginning of intense vaporization (T_H is substantially higher than T_m).

According to (5), at $r_0 \leqslant 2x_0$, the body is practically heated through, and at the height h_H it is already entirely melted. Under the action of aerodynamic pressure and of forces of superficial tension the molten body acquires an oblate shape. Let us estimate the value of deformation, assuming that the drop has the shape of an ellipsoid of revolution with its minor axis in the direction of motion.

The difference in pressures created by the forces of superficial tension in the longitudinal and transverse cross sections of the drop must be equal to the aerodynamic pressure. With the aid of the Laplace formula we obtain

$$\sigma\left(\frac{a^2}{b^2}+\frac{1}{a}\right)-\frac{2\sigma}{a}=\Gamma\rho v^2, \qquad (9)$$

where ρ is the superficial tension coefficient ; σ is the drag coefficient ; **a** and **b** are respectively the major and minor ellipsoid semiaxis; $a^2b = r^3$ (r being the radius of the drop). Then

$$\left(\frac{a}{r}\right)^5-\frac{r}{a}=\frac{\Gamma r v^2\rho}{\sigma}. \qquad (10)$$

Neglecting in the left hand part of Eq. (10) the term r/a (which leads to a certain lowering of the value of deformation); we obtain

$$a=(\Gamma v^2\rho/\sigma)^{1/5}r^{6/5}.$$

The equation of meteor body vaporization is

$$\frac{dM}{dt}=-\frac{\Lambda}{2Q}Sv^3\rho=-\frac{\pi\Lambda}{2(Q-Q_H)}v^{19/5}\left(\frac{\Gamma}{\sigma}\right)^{2/5}r^{12/5}\rho^{7/5}, \qquad (12)$$

where M is the mass of the body. For an isothermic atmosphere Eq. (12) may be rewritten in the form

$$\frac{dr}{r^{2/5}}=-\frac{\Lambda H v^{14/5}}{8(Q-Q_H)\delta\cos z}\left(\frac{\Gamma}{\sigma}\right)^{2/5}\rho^{2/5}d\rho. \qquad (13)$$

Neglecting the meteor body deceleration in the process of vaporization, we obtain

$$r^{3/5}=-\frac{3\Lambda H v_0^{14/5}}{56(Q-Q_H)\delta\cos z}\left(\frac{\Gamma}{\sigma}\right)^{2/5}(\rho^{7/5}-\rho_H^{7/5})+r_0^{3/5}. \qquad (14)$$

From (12) and (14) we found the curve for meteor's light force

$$I=-\frac{kv_0^2}{16\pi}\frac{dM}{dt}=$$

$$=\frac{k\Lambda}{16(Q-Q_H)}\left(\frac{\Gamma}{\sigma}\right)^{2/5}v_0^{29/5}\rho^{7/5}\left[r_0^{3/5}-\frac{3\Lambda H v_0^{14/5}}{56(Q-Q_H)\delta\cos z}\left(\frac{\Gamma}{\sigma}\right)^{2/5}(\rho^{7/5}-\rho_H^{7/5})\right]^4, \qquad (15)$$

where k is the luminosity factor.

For a sufficiently strong deformation the drop becomes unstable, The questions of stability of liquid drops in a gas flow have been considered in a series of experimental and theoretical works [5 – 9]. The drop stability is characterized by the Weber number

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$$\mathrm{We} = \Gamma \rho v^2 r / \sigma.$$

For a viscous liquid the critical value of We is, according to [8. 9],

$$\mathrm{We}_0 \approx 6{,}5.$$

At $\mathrm{We} > \mathrm{We}_0$ the drop splits up.

From (8) and (14) we find the limit value of the initial radius r_0' of the drop, which preserves the stability in the vaporization process:

$$r_0' = {}^3/_4 \sigma \mathrm{We}_0 / \Gamma \rho_{\text{н}} v_0^2.$$

At $r_0 < r_0'$ the drop does not split up. In this case a certain shortening of the meteor trail takes place on account of increase at the expense of deformation of the median cross section.

All meteor bodies with initial radii $r_0 > r_0'$ split up: at the same time: 1) if ${}^4/_3 r_0' \leqslant r_0 \leqslant 2x_0$, the splitting takes place already at the height of initial intensive vaporization; 2) if $r_0' \leqslant r_0 < {}^4/_3 r_0'$ and $r_0 \leqslant 2x_0$, the splitting takes place when the radius of the drop reaches the critical value corresponding to the condition $\mathrm{We} = \mathrm{We}_0$; 3) if $r_0 \geqslant {}^4/_3 r_0'$ and $r_0 > 2x_0$, the splitting takes place after the body has been melted through; 4) if $r_0' \leqslant r < {}^4/_3 r_0'$ and $r_0 > 2x_0$, the splitting takes place after the drop has been melted through and the radius has attained the critical value corresponding to $\mathrm{We} = \mathrm{We}_0$.

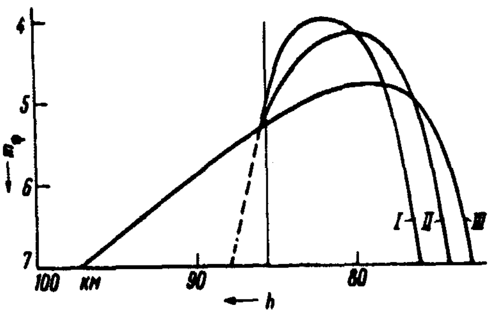

Fig. 1

We shall consider, as an example, the vaporization of a dense stone meteoric body with $r_0 = 2x_0$ and $v_0 = 15$ km/sec. According to [10], for stone meteoric bodies $\lambda = 2 \cdot 10^5$ erg/cm·sec·deg, $b = 0.08\ \mathrm{sec}^{1/2}$, $\delta = 3.4$ g/cm^3, $Q = 6 \cdot 10^{10}$ erg/g, $\sigma = 360$ dyne/cm, $k = 1.1 \cdot 10^{-3}$. Assuming $A = \Gamma = 1$ and the mean value $\cos z = 2/3$, we find $r_0 = {}^4/_3 r_0'$, that is, the body splits up already at the height of initial intensive vaporization. The computations conducted show that the shape of the curve for the force of light depends comparatively little on the assumed droplet dimensions, for which the body splits up. If the sizes of drops are sufficiently great, the droplets soon become unstable and split up in parts in their turn.

The curve for the light force I of Fig. 1 is computed in the assumption that the drop splits up into a minimum number of droplets, each of which remaining stable in the process of vaporization. For comparison we have plotted : II – for the light force curve computed according to (15) without taking into account the splitting; III – the light force curve (1), assigned by the simplest physical theory of meteors.

**** THE END ****

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