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Abstract

Full Text

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Astronomy

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ON THE CHARACTER OF THE FRAGMENTATION OF METEORIC BODIES

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Since 1964, special photographic observations of meteors have been carried out in Dushanbe and Odessa, using the method of instantaneous exposure. The aim of these observations is to study the processes of evaporation, luminosity, and fragmentation of meteors. To date, instantaneous photographs of 89 meteors have been obtained. Some of them have been processed and the corresponding results published (*1, 2*). Here we present the results of processing two meteors that fragmented into several pieces.

Fig. 1. Fragmentation of the meteor of 12 VIII 1966.

Figure 1 shows part of the instantaneous photographs of a Perseid that flew over Dushanbe on 12 VIII 1966. The initial (extra-atmospheric) velocity and mass of this meteor were respectively 60.8 km/sec and somewhat more than 20 g. The duration of its flight was about 1 sec. Table 1 gives the values of the velocity, deceleration, and mass of the meteoric body as a function of height, of the ablation coefficient

Table 1

H, km	v, km/sec	$\dot{v}_{\text{obs}}$, km/sec^2	m, g	$\sigma \cdot 10^{12}$, cm^{-2} sec^2	$\dot{v}_1$, km/sec^2	$\dot{v}_2$, km/sec^2
100.5	60.7	−0.332	18.4	0.49	−0.238	−0.691
97.4	60.7	−0.491	16.8	0.37	−0.445	−0.947
94.7	60.6	−0.687	14.5	0.60	−0.778	−1.921
91.6	60.5	−1.012	9.2	0.89	−1.714	−4.203
88.0	60.4	−1.571	3.2	6.92	−4.487	−10.768

Fig. 2. Linear dimensions and displacement of meteor fragments

Figure 2: Fig. 2. Linear dimensions and displacement of meteor fragments

$\sigma = (\ln m_\infty^2 - \ln m^2)/(v_\infty^2 - v^2)$

and of the theoretical decelerations $\dot{v}_1$ and $\dot{v}_2$, calculated respectively without taking into account and taking into account the reaction of evaporating molecules.

The increase in the ablation coefficient indicates progressive fragmentation of the meteoric body. On the other hand, comparison of the observed deceleration with its theoretical values (if systematic observational errors are neglected) makes it possible to conclude that the parent body did not pulverize, but fragmented into separate, comparatively large pieces (the observed deceleration does not exceed the theoretical ⋯

tical value calculated for a nonfragmenting meteor body). This is also indicated, in particular, by the negative value of the fragmentation index for this meteor,

$$\chi = \frac{d}{ds} \lg \frac{v_{\text{obs}}}{v_{\text{theor}}},$$

where s is the mass-loss parameter

$$s = \lg \left(\frac{m_\infty}{m} - 1 \right).$$

It is seen from Fig. 1 that the original meteoric body split into three fragments (a, b, and c). Here a is apparently the remnant of the parent meteoric body; fragments b and c simultaneously separated from a at approximately an altitude of 96 km. Being more massive, fragment b lagged behind a somewhat less than c. In turn, fragment b subsequently shed first one (b') and then a second (b'') fragment. Two more fragments (a' and a'') were ejected from a at an altitude of about 87–85 km. The images of the individual fragments appear after a certain lengthening of the image of the parent meteor: the detachment of fragments b and c corresponds to the lengthening of stroke A, the detachment of fragment b' corresponds to stroke B, etc.

Fig. 2. Linear dimensions and displacement of meteor fragments

Figure 2 gives the displacements of the fragments relative to the parent body a as functions of time. The vertical lines show the linear dimensions of meteors a and b. It is clearly visible how the lengthening of a stroke passes into the separation of images.

The luminosity of the fragments begins immediately after their separation from the parent body. In this connection it is interesting to estimate the time required for a "cold" fragment to reach the temperature of intense evaporation. For this purpose it is necessary to solve the heat-conduction equation

$$\partial T/\partial t - \beta^2 \partial^2 T/\partial x^2 = \frac{1}{2}\Lambda \rho_0 v^3 e^{kt} \frac{\delta(x)}{\rho_m c} \tag{1}$$

under the boundary conditions

$$T(0,0) = T_0, \qquad T(0,\Delta t) = T_v. \tag{2}$$

Here $\beta^2 = \lambda/\rho_m c$; $k = v\cos z/H$; λ is the thermal conductivity and ρ_m the density of the meteoric body; c is the specific heat; Λ is the heat-transfer coefficient; ρ_0 is the atmospheric density at the altitude where the fragment separates; v is the meteor velocity; z is the zenith distance of the radiant; H is the height of the homogeneous atmosphere, and $\delta(x)$ is the δ-function, vanishing in any neighborhood Δx of the point $x = 0$

$$\left(\int_{-\Delta x}^{+\Delta x} \delta(x)\,dx = 1\right).$$

Solving (1) under the boundary conditions (2), we obtain a formula that makes it possible to calculate the time required for the temperature of the surface of the meteoric body to rise from T_0 to T_v:

$$\operatorname{erf}\left(\sqrt{k\Delta t}\right) = \frac{4\beta\rho_m c}{\Lambda \rho_0 v^3 e^{k\Delta t}} \sqrt{\frac{v\cos z}{H}}\,(T_v - T_0), \tag{3}$$

where T_0 is the initial temperature of the meteoric body, and T_v is the temperature of intense evaporation.

For our meteor, $\cos z = 0.49$; at the fragmentation height $\rho_0 = 10^{-9}$ g/cm^3 and $H = 6.43 \cdot 10^5$ cm. Taking $T_v - T_0 = 2000^\circ$K, we obtain, for $\Lambda = 1$ and $\Lambda = 0.1$, respectively, the values $\Delta t = 0.009$ s and $\Delta t = 0.23$ s. In 0.009 s the fragment, in the "cold" state, does not have time to lag noticeably behind the parent meteoric body; the second value (0.23 s) is sufficient for a noticeable lag of the fragment to be detected. During this time the fragment lags behind the parent body without radiating. This means that the corresponding image of it would appear suddenly at some distance from the leading meteoric body, which in fact is not observed: in Figs. 1 and 2 one sees a gradual elongation of the tail of the corresponding meteoric body and its transition into a separate image. Consequently, assuming that the fragments separate "cold," we arrive at the conclusion that $\Lambda \simeq 1$.

In addition, it can be shown that the meteoric body at the moment of fragmentation was moving in a regime close to the free-molecular one. For this, let us calculate the Knudsen number $\mathrm{Kn} = l/d_0$, where l is the mean free path of the molecules and d_0 is the characteristic transverse dimension of the body.

At the height of the first fragmentation (about 96 km), $l = 8.16$ cm (^{3}), and (for a meteoric-body density $\rho_m = 1$ g/cm^3) $d_0 = 2.6$ cm (see Table 1). Consequently, $\mathrm{Kn} = 3.1$, i.e., greater than the critical value ($\mathrm{Kn} = 2$ (^{4})), corresponding to the transition from a slip-flow regime to a free-molecular-flow regime. For the normal density of a meteoric body (3.5–7.8 g/cm^3), $\mathrm{Kn} > 4.5$–6, which also corresponds to free-molecular flow.

Since the motion of the meteoric body takes place in the free-molecular regime, two forces act on the frontal surface of the meteoric body: 1) the hydrodynamic pressure of the impinging air molecules and 2) the reactive force arising as a result of evaporation of meteoric material. The first force at the fragmentation height is equal to $\pi r^2 \rho v^2 = 1.9 \cdot 10^5$ dynes, while the second,

$$\frac{4}{9}\frac{dm}{dt}v_T$$

(v_T is the thermal velocity of the evaporating molecules) is approximately $2 \cdot 10^6$ dynes. Under the influence of these forces only very brittle meteoric bodies can fragment. Brittle deformation also depends on the amount of energy absorbed per unit time. With intense evaporation, the external energy is spent entirely on ablation of the surface layer; this energy almost does not penetrate inside.

Jones and Kaiser (^{5}) suggest that meteoric bodies become brittle at great height during their sudden heating (even before melting) as a result of thermal shock. They apply equations by means of which they calculate the elastic stresses arising inside the meteoric body under thermal shock, without showing, however, that such thermal shock actually takes place. If, in our case, cracks had arisen in the meteoric body before melting of the surface layer, then it would have fragmented at a greater height, at the very beginning of intense evaporation, as occurs for faint meteors. In reality, fragmentation occurred more than 0.5 s after the appearance of the meteor. During their intense evaporation, as was shown by B. Yu. Levin (^{6}) and emphasized above, all the energy is spent on evaporation and, with the exception of a thin surface layer, the meteoric body remains cold. In this case the temperature gradient inside the meteoric body is so insignificant that it cannot lead to splitting.

Usually the breakup of a meteoric body into several fragments occurs after the flare of the meteor caused by sudden evaporation of the molten layer. Such instantaneous evaporation gives rise to an elastic wave directed into the meteoric body, and this, in turn, may lead to the spalling of fragments from the rear part of the meteoric body (^{7}).

Another cause of fragmentation of the meteoric body may be the release-

conversion of internal energy (evaporation of volatile inclusions). The role of this mechanism is especially clearly manifested in the fragmentation of meteor

No. 407, photographed in Odessa on 8 VIII 1965 (speed at the beginning of the trajectory 20 km/sec, initial mass approximately 130 g). On careful study of the photographs of this meteor it is seen* that one of the fragments, immediately after fragmentation, moves noticeably faster than the original parent body. The fragmentation occurred at an altitude of about 73 km; the aerodynamic pressure at this altitude was $\rho v^2 = 2.3 \cdot 10^5$ dyn/cm^2; the speed of the meteor immediately before the onset of fragmentation was 19.5 km/sec. The meteor broke into two parts. Measurements showed that the speed of one of the fragments was 1.4 ± 0.3 km/sec greater than the speed of the parent meteoric body. Such acceleration of a fragment can be explained only by the release of internal energy.

Fragmentation of meteors into two or more parts has been observed visually more than once and has been studied visually ([8]). At various times photographs of fragmented meteors were obtained; they made it possible to estimate the velocities of individual fragments. In 1953 Z. Ceplecha obtained, for the normal component of the velocity of a fragment of meteor 131a, the value $v_n = 0.72$ km/sec ([9]). For the fireball of 11 V 1955, one of the authors ([10]) obtained $v_n = 0.20$ km/sec. These quantities differ little from the velocity obtained for the fragment of meteor 407, photographed with the aid of an obturator installation, which made it possible to measure the relative velocity of the fragment, which, of course, is greater than its normal component.

Thus, from the example of the meteors considered above, it is evident that fragmentation processes have a complex character and testify to the special structure of meteoric bodies of cometary origin.

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* The photographs will be published in *Coll. Meteoritics*, vol. 28.

Note: Figure translations are in progress. See original paper for figures.