SESSION 4

Chairman: V. V. Fedynskij

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19. EVAPORATION AND DECELERATION OF SMALL METEOROIDS

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Knowledge of altitude and ionization curves of faint meteors is of great importance for the calculation of meteor detectability during radar observations (Greenhow and Hall, 1960; Lebedinec, 1963). Greenhow (1963), using the simplest physical theory of meteors (Herlofson, 1948) for altitude calculations, arrived at a conclusion that radar observations of very faint meteors were impossible for practically any radar power. The simplest physical theory of meteors is used for calculations of radar-meteor detectability by almost all the authors. Lebedinec (1963) has shown that this theory is inapplicable in the case of faint meteors since one should take into account energy losses caused by thermal radiation from the meteoroid surface.

The problem of evaporation of very small meteoroids producing meteors fainter than about $+8^{\mathrm{m}}$ has been solved approximately (Lebedinec, 1963, 1964) taking into account energy losses caused by thermal radiation from the body surface. For these calculations it was assumed that meteoroid surface temperature after the beginning of intensive evaporation does not change; deceleration was taken into account approximately. The calculated altitudes of very faint meteors differ greatly from the values adopted by other authors. For example, for a meteor $+20^{\mathrm{m}}$ with an initial velocity $v_0 = 40$ km/sec the maximum evaporation altitude is $h_m = 102$ km (Lebedinec, 1963, 1964); while Greenhow (1963) and other authors adopted $h_m = 138$ km for such meteors. In this connection it is very interesting to obtain the exact solution of the problem of evaporation and deceleration of small meteoroids free from the limitations we imposed before and extend it for a wider range of meteoroid masses.

Let us consider the movement in the atmosphere of a small black meteoroid of spherical shape and heated through. Due to collisions with atmospheric molecules the meteoroid receives per unit time the following energy (Kaščeev *et al.*, 1967)

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \Lambda \frac{A}{2} M^{2/3} \delta^{-2/3} \rho v^3, \tag{1}$$

where Λ = heat-transfer coefficient; A = form factor (for the sphere $A = 1{\cdot}21$); M, δ, v = mass, density, and velocity of the meteoroid; ρ = atmospheric density.

The energy received by the meteoroid is spent: for heating

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_1 = CM \frac{\mathrm{d}T}{\mathrm{d}t}, \tag{2}$$

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evaporation

$$\left(\frac{dE}{dt}\right)_2 = 4AM^{2/3}\delta^{-2/3}Q\Delta M\,, \tag{3}$$

and thermal radiation from the body surface

$$\left(\frac{dE}{dt}\right)_3 = 4AM^{2/3}\delta^{-2/3}\sigma T^4\,. \tag{4}$$

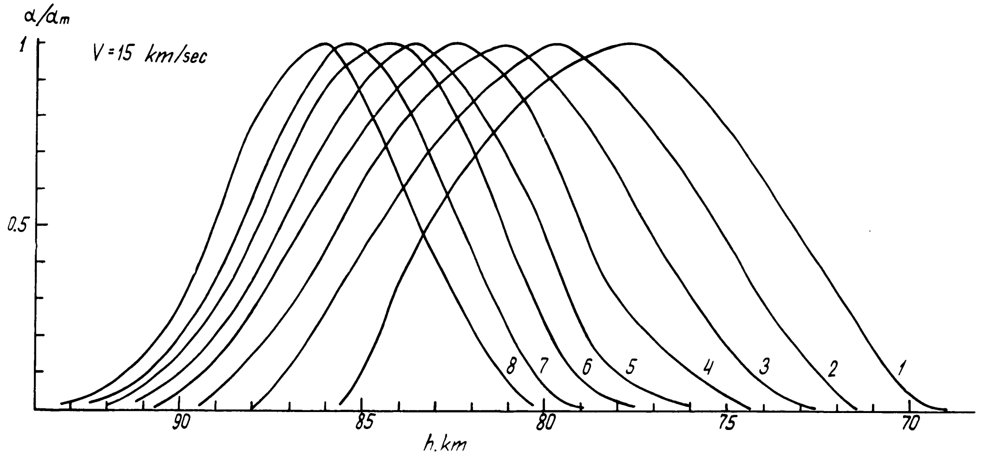

FIG. 1. *Ionization curves of meteors produced by meteoroids with masses: (1) 1×10^{-2} g, (2) $3{\cdot}16\times10^{-3}$ g, (3) 1×10^{-3} g, (4) $3{\cdot}16\times10^{-4}$ g, (5) 1×10^{-4} g, (6) $3{\cdot}16\times10^{-5}$ g, (7) 1×10^{-5} g, (8) $3{\cdot}16\times10^{-6}$ g; $\cos z = \frac{2}{3}$; $v_0 = 15$ km/sec.*

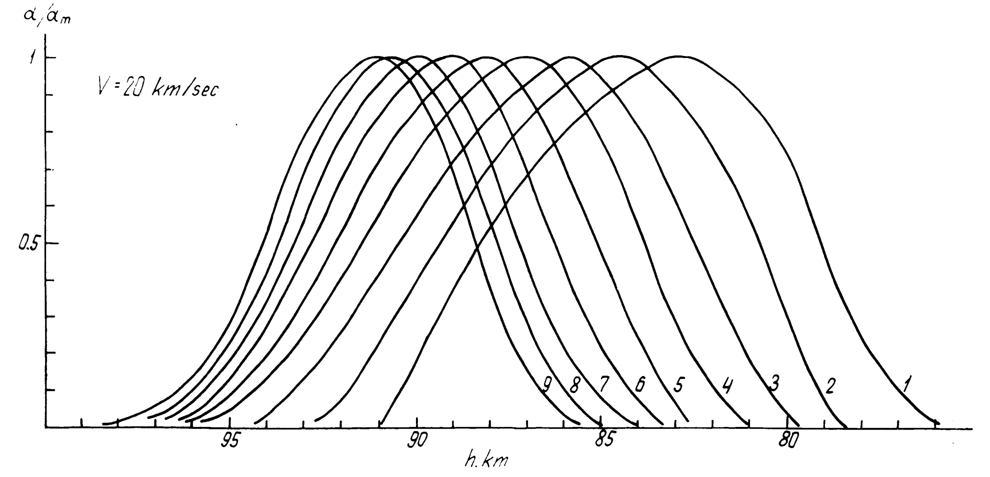

FIG. 2. *Ionization curves of meteors produced by meteoroids with masses: (1) $3{\cdot}16\times10^{-3}$ g, (2) 1×10^{-3} g, (3) $3{\cdot}16\times10^{-4}$ g, (4) 1×10^{-4} g, (5) $3{\cdot}16\times10^{-5}$ g, (6) 1×10^{-5} g, (7) $3{\cdot}16\times10^{-6}$ g, (8) 1×10^{-6} g, (9) $3{\cdot}16\times10^{-7}$ g; $\cos z = \frac{2}{3}$; $v_0 = 20$ km/sec.*

Here C = heat capacity of meteor substance; T = meteoroid temperature; Q = latent heat of evaporation; σ = Stefan-Boltzmann constant; ΔM = meteor mass evaporating at temperature T per unit time from the body-surface unit.

Dependence of evaporation rate on temperature is given usually as (Kaščeev *et al.*, 1967)

$$\Delta M = C_1 T^{-1/2} e^{-C_2/T}, \tag{5}$$

where C_1, C_2 are constants for the given substance in the given temperature range.

In the case of isothermal atmosphere

$$\mathrm{d}t = \frac{H \mathrm{d}\rho}{\rho v \cos z}, \tag{6}$$

where H = atmospheric scale height, z = zenith angle of the meteor path.

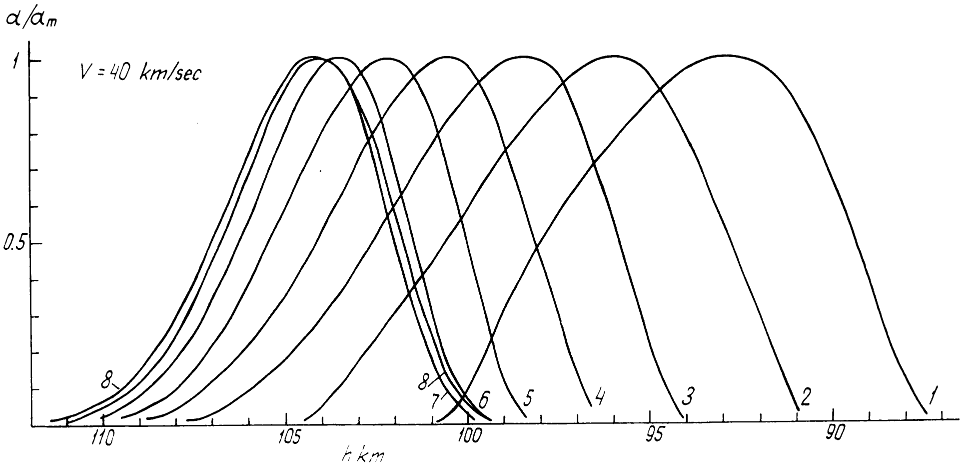

FIG. 3. *Ionization curves of meteors produced by meteoroids with masses: (1) 1×10^{-3} g, (2) 1×10^{-4} g, (3) 1×10^{-5} g, (4) 1×10^{-6} g, (5) 1×10^{-7} g, (6) 1×10^{-8} g, (7) 1×10^{-9} g, (8) $3{\cdot}16 \times 10^{-10}$ g; $\cos z = \frac{2}{3}$; $v_0 = 40$ km/sec.*

From (1)–(6) we obtain the energy equation:

$$\frac{\Lambda}{8} \rho v^3 = \sigma T^4 + C_1 Q T^{-1/2} e^{-C_2/T} - \frac{C M^{1/3} \delta^{2/3} \rho v \cos z}{4AH} \frac{\mathrm{d}T}{\mathrm{d}\rho}, \tag{7}$$

and the evaporation equation:

$$\frac{\mathrm{d}M}{\mathrm{d}\rho} = -\frac{4AHM^{2/3}}{\rho v \cos z \delta^{2/3}} C_1 T^{-1/2} e^{-C_2/T}. \tag{8}$$

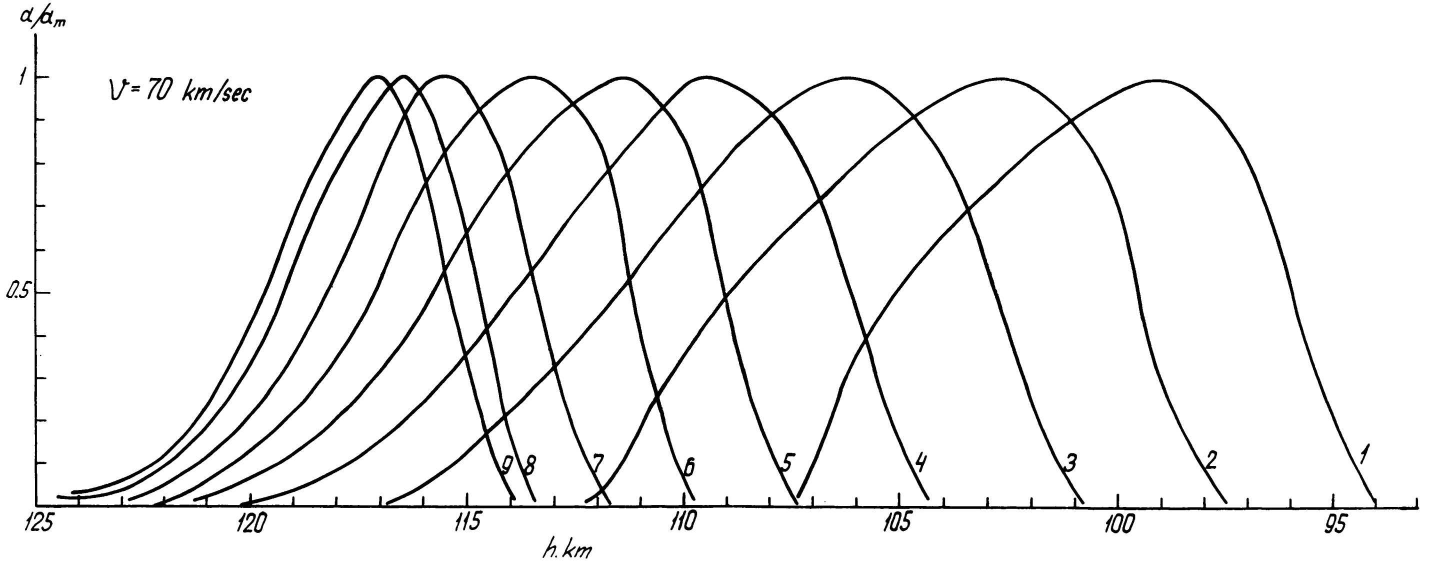

FIG. 4. *Ionization curves of meteors produced by meteoroids with masses: (1) 1×10^{-3} g, (2) 1×10^{-4} g, (3) 1×10^{-5} g, (4) 1×10^{-6} g, (5) 1×10^{-7} g, (6) 1×10^{-8} g, (7) 1×10^{-9} g, (8) 1×10^{-10} g, (9) 1×10^{-11} g; $\cos z = \frac{2}{3}$; $v_0 = 70$ km/sec.*

The deceleration equation of the meteoroid (Kaščeev *et al.*, 1967) is

$$\frac{dv}{d\rho} = -\frac{\Gamma AHv}{M^{1/3}\delta^{2/3}\cos z}, \tag{9}$$

where Γ is the drag coefficient.

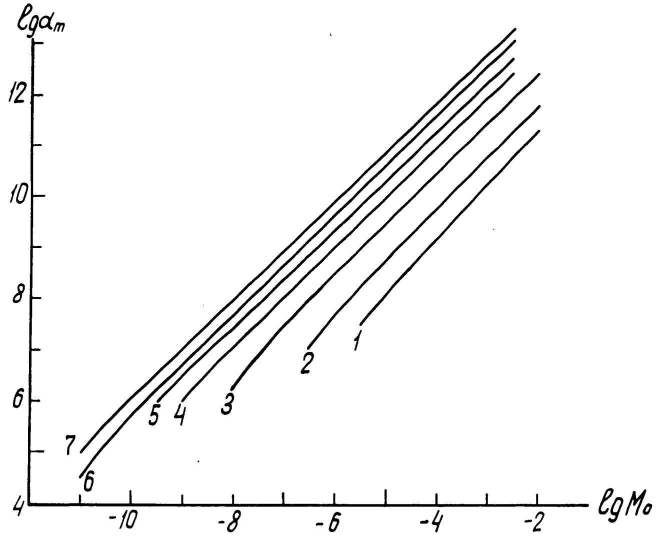

FIG. 5. *Dependence of α_m on meteoroid mass at velocities: (1) 15 km/sec, (2) 20 km/sec, (3) 30 km/sec, (4) 40 km/sec, (5) 50 km/sec, (6) 60 km/sec, (7) 70 km/sec.*

The ionization equation is

$$\alpha = \frac{\beta\rho\cos z}{\mu m_H H}\frac{dM}{d\rho}, \tag{10}$$

where β is ionization probability, that is, the mean number of free electrons produced by one evaporated meteor atom, μ is mean atomic weight of the meteor substance, m_H is hydrogen atom mass.

Thus, the problem of heating, evaporation, and deceleration of the heated-through small meteoroids reduces to the solution of a system of differential Equations (7)–(9). According to Kaščeev *et al.* (1967) the boundary-radius value of the practically heated-through meteoroid is

$$r_0' = 2b\sqrt{\frac{H}{v_0\cos z}}, \tag{11}$$

the boundary radius value of the melted meteoroids which preserve stability in the

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process of evaporation is

$$r_{g0}^2 = \frac{27\sigma\Lambda H W e_0}{128\Gamma\delta Q_H \cos z}. \tag{12}$$

Here b = thermal-conductivity coefficient; σ = surface-tension coefficient; Q_H = heating energy of 1 g of meteor substance up to the temperature of the beginning of intensive

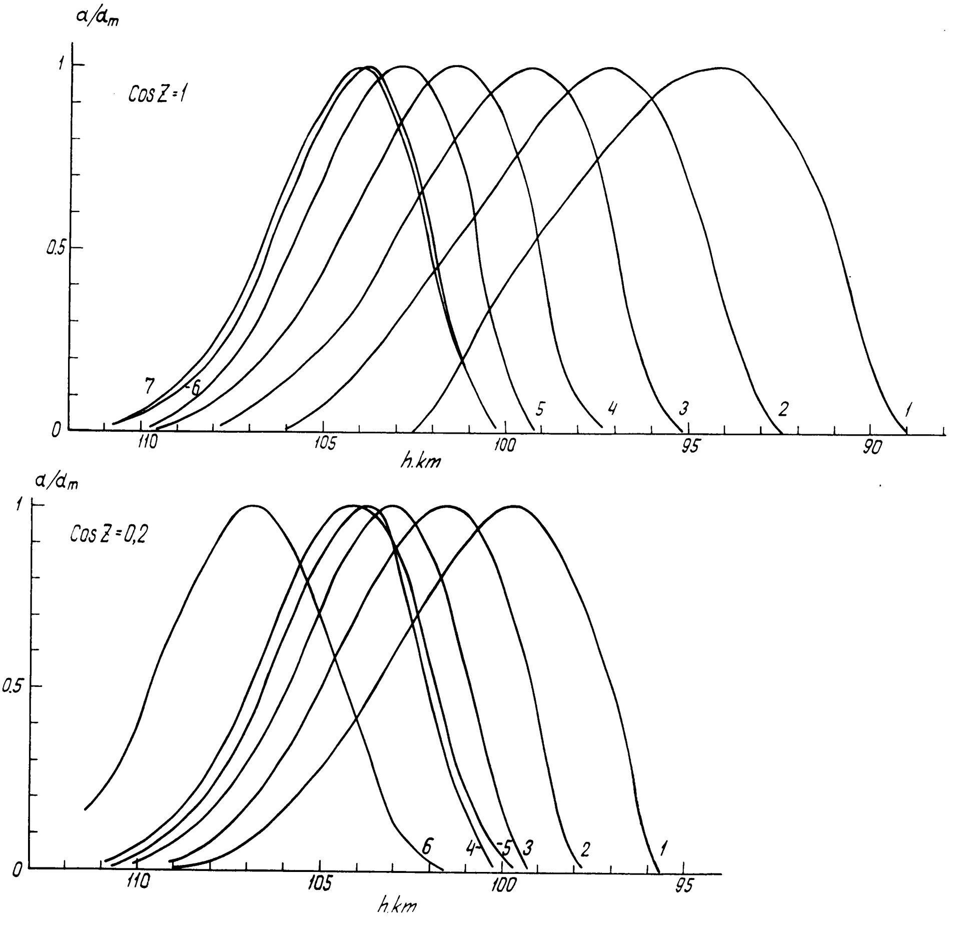

FIG. 6. *Ionization curves of meteors produced by meteoroids with masses: (1) 1×10^{-4} g, (2) 1×10^{-5} g, (3) 1×10^{-6} g, (4) 1×10^{-7} g, (5) 1×10^{-8} g, (6) 1×10^{-9} g, (7) $3{\cdot}16 \times 10^{-10}$ g; $v_0 = 40$ km/sec; $\cos z = 1$, $\cos z = 0{\cdot}2$.*

evaporation; We_0 = critical value of Weber's number: $We = (\Gamma\rho r v^2)/\sigma$ (where r is the radius of the body) when the melted meteor body begins to break up; $We_0 \approx 6$. For meteoroids with $r_0 < r_{g0}$ it is possible to neglect fragmentation.

Thus, the Equation system (7)–(9) may be used for small meteoroids, the initial radii of which satisfy the conditions: $r_0 < r_0'$ and $r_0 < r_{g0}$. Initial conditions are the following:

For $\rho = 0$:

$$T = T_0, \quad M = M_0, \quad v = v_0, \tag{13}$$

where T_0 is the equilibrium temperature of meteoroids at a distance of 1 AU from the Sun.

The Equation system (7)–(9) under initial conditions (13) has been solved, by the Runge-Kutta method with automatic step choice, by the computer 'Minsk-2' for different values of M_0, v_0 and $\cos z$.

The following parameter values used in (7)–(9) were adopted for stone meteoroids:

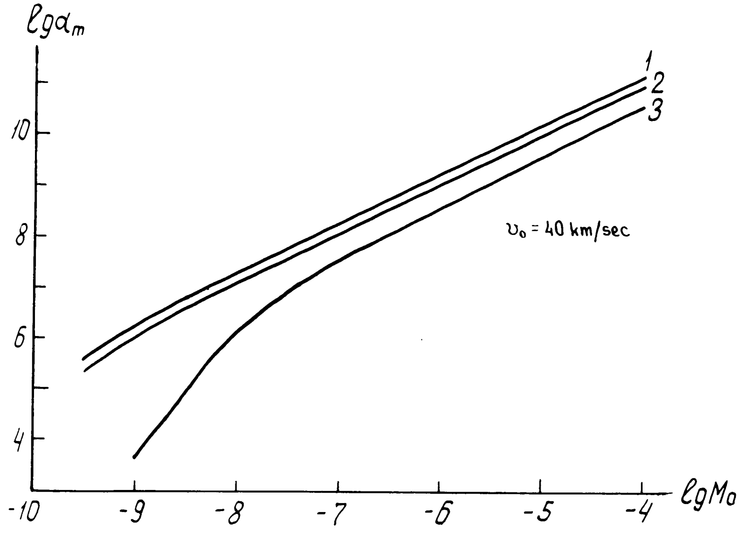

FIG. 7. *Dependence of α_m on meteoroid mass: (1) $\cos z = 1$, (2) $\cos z = \frac{2}{3}$, (3) $\cos z = 0{\cdot}2$; $v_0 = 40$ km/sec.*

$\Lambda = \Gamma = 1$; $\delta = 3{\cdot}5$ g/cm^3; $C_1 = 6{\cdot}92 \times 10^{10}$ g/cm^2 sec and $C_2 = 5{\cdot}78 \times 10^4$ deg (Lebedinec and Portnjagin, 1967); $C = 10^7$ erg/g deg; $Q = 6 \times 10^{10}$ erg/g; $Q_H = 2 \times 10^{10}$ erg/g; $b = 0{\cdot}1$ cm/sec$^{1/2}$, $\beta = 4 \times 10^{-25} v^{7/2}$ (Kaščeev *et al.*, 1967).

Figures 1–4 show the curves of ionization of meteors caused by meteoroids with different masses for $\cos z = \frac{2}{3}$ and velocities of 15, 20, 40, and 70 km/sec. Figure 5 shows the dependence of linear electron density of the meteor trail at an altitude of maximum ionization, α_m, on M_0 at different velocities and $\cos z = \frac{2}{3}$. The ionization curves are given in Figure 6 for $v_0 = 40$ km/sec, different values of M_0 and two values of $\cos z$ (1 and 0·2). The dependence of α_m on M_0 is presented in Figure 7 for $v_0 = 40$ km/sec and three values of $\cos z$: 1, $\frac{2}{3}$ and 0·2.

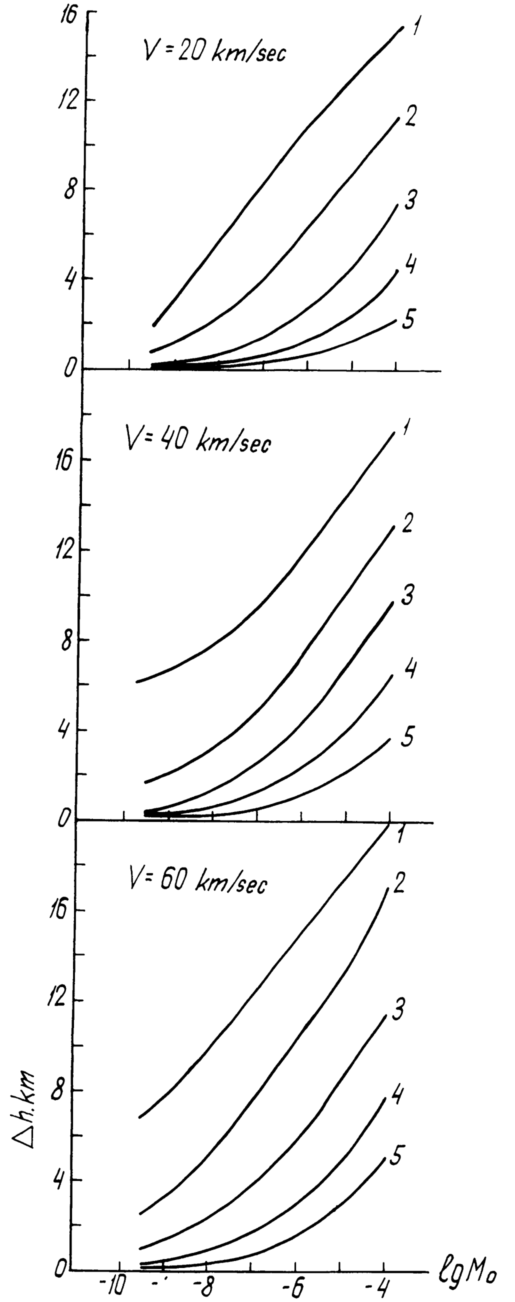

FIG. 8. *Mass dependence of height intervals where liquid droplet mass blown off from the large meteoroid surface decreases as much as 100 times: (a) at* $v_0 = 60$ *km/sec and heights of separation: (1) 117 km, (2) 112 km, (3) 107 km, (4) 103 km, (5) 99 km; – (b) at* $v_0 = 40$ *km/sec and heights of separation: (1) 108 km, (2) 104 km, (3) 100 km, (4) 97 km, (5) 92 km; – (c) at* $v_0 = 20$ *km/sec and heights of separation: (1) 96 km, (2) 92 km, (3) 89 km, (4) 85 km, (5) 81 km;* $\cos z = \frac{2}{3}$.

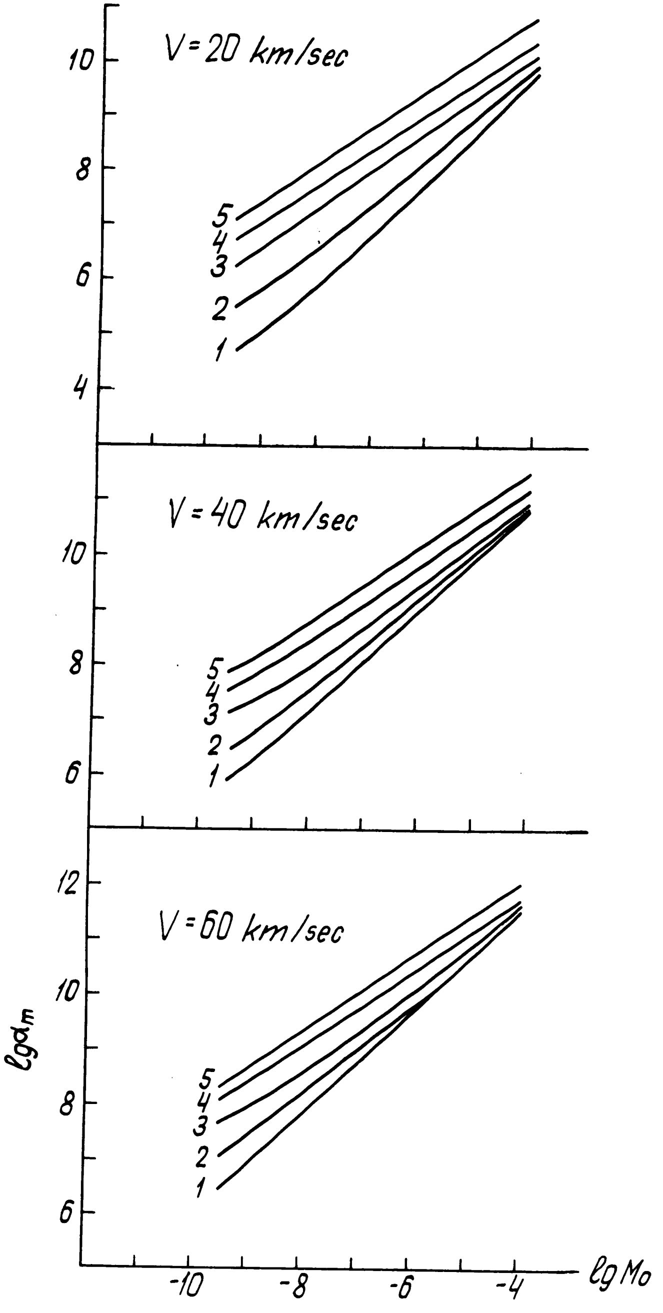

FIG. 9. *Dependence of* α_m *on the initial mass* M_0*: (a)* $v_0 = 60$ *km/sec at separation heights: (1) 117 km, (2) 112 km, (3) 107 km, (4) 103 km, (5) 92 km – (b)* $v_0 = 40$ *km/sec at separation heights: (1) 108 km, (2) 104 km, (3) 100 km, (4) 97 km, (5) 92 km – (c)* $v_0 = 20$ *km/sec at separation heights: (1) 96 km, (2) 92 km, (3) 89 km, (4) 85 km, (5) 81 km.*

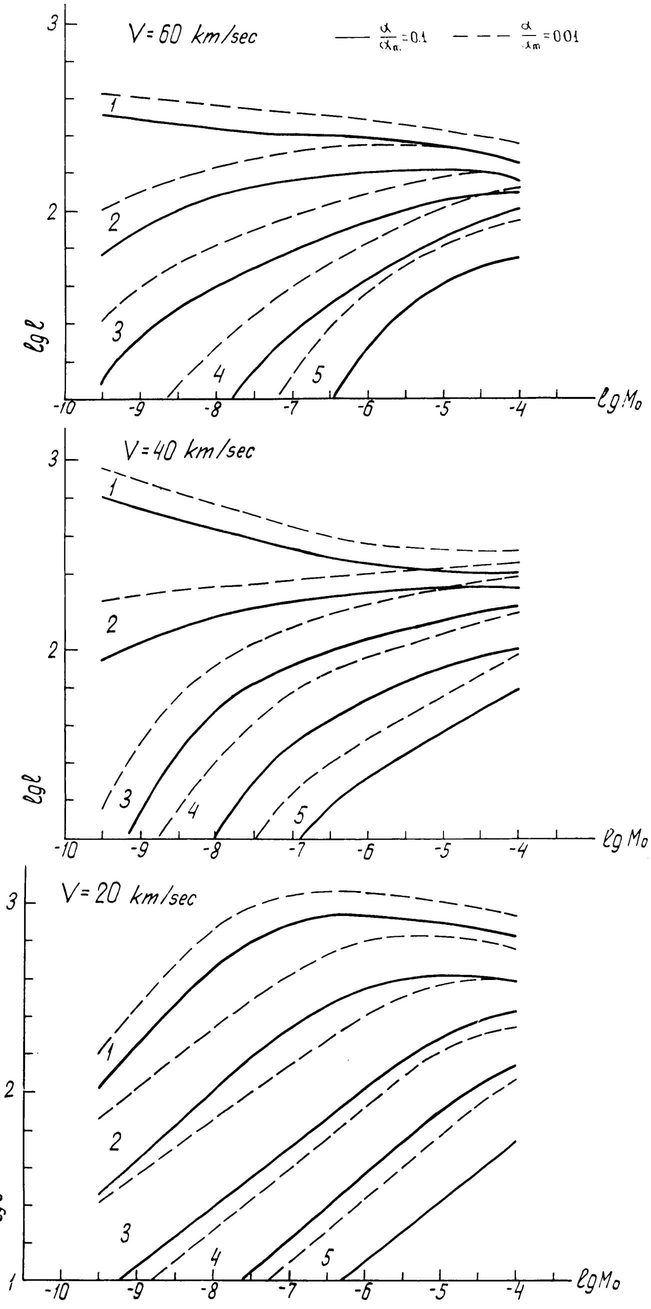

FIG. 10. *Dependence of meteor 'tail' length on droplet mass: (a)* $v_0 = 20$ *km/sec at separation heights: (1) 96 km, (2) 92 km, (3) 89 km, (4) 85 km, (5) 81 km – (b)* $v_0 = 40$ *km/sec at separation heights: (1) 108 km, (2) 104 km, (3) 100 km, (4) 96 km, (5) 92 km – (c)* $v_0 = 60$ *km/sec at separation heights: (1) 117 km, (2) 112 km, (3) 107 km, (4) 103 km, (5) 99 km. – Solid lines are curves for* $\alpha/\alpha_m = 0{\cdot}1$*, dotted lines are curves for* $\alpha/\alpha_m = 0{\cdot}01$*.*

Figures 1–4 show that the trail length of meteors decreases when meteoroid mass diminishes. The height where intensive evaporation begins does not vary much. Comparison with our earlier work (Lebedinec, 1963, 1964) reveals satisfactory agreement between the previously obtained approximate solution and the exact one obtained in the present paper. For example, for a meteor $+15^{m}$ at $v_0=40$ km/sec and $\cos z=\frac{2}{3}$, the height of maximum ionization $h_m=102$ km is obtained. This coincides with the value obtained earlier (Lebedinec, 1964) and differs greatly from $h_m=128$ km adopted by Greenhow (1963) according to the oversimplified physical theory of meteors. Regard for meteoroid temperature increase during evaporation results in some increase of trail length of faint meteors. The height difference between the beginning and end of the trail decreases slightly and the height where intensive evaporation begins is almost constant with the radiant zenithal distance (Figure 6).

The Equation system (7)–(9) can also be used to study evaporation and deceleration of small particles separating from larger meteoroids at different heights. We have obtained the solution for particles of various masses, velocities and separation height (h_0). Figure 8 gives the height intervals where the mass of liquid droplets blown off from the surface of a large meteoroid decreases as much as 100 times (for $\cos z=\frac{2}{3}$, three values of $v_0=20$, 40 and 60 km/sec, $10^{-10}<M_0<10^{-4}$ and for different separation heights). The dependence of α_m on M_0 for meteor trails produced by separated droplets is given in Figure 9. These data allow one to estimate particle sizes separated during meteor bursts.

The loss of mass and velocity of the separating droplets is considerably faster in comparison to the parent body. Neglecting the parent-body deceleration one may estimate the length l of the meteor 'tail', which appears as a result of blowing-off of droplets. The dependence of l on the droplet mass for different meteor velocities and heights of separation is shown in Figure 10. The 'tail' lengths are in good agreement with observed results (Babadžanov and Kramer, 1965).

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DISCUSSION

Fedynskij: The modern techniques of meteor investigations give us information which is not yet sufficient for the determination of the main parameters of the solid component of the interplanetary matter with the desirable accuracy. Such quantities as mass and space density of this matter can be obtained only approximately. For progress in this field it is necessary to be more precise in our presentations about the structure and the composition of meteor bodies, as well as their interaction with the Earth's atmosphere. This problem has existed in meteor physics for many years. But now it is essentially important in connection with the investigations of cosmic space and the need for coordinating the information on the solid component of interplanetary matter obtained from the observations at the Earth, with that from cosmic space.