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On a meteor mechanism of dust formation in the upper atmosphere

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Abstract

Mechanism of dust formation in high atmosphere as a quasi-continuous dispersion from the melted layer of meteoroid is considered. Elementary theory of the meteor body spraying is proposed for the case of overtaking melting. The similarity in hydrodynamic conditions for liquid drop and for meteoroid is used for the case when the meteoroid trajectory is slow-sloped. The "gradient instability" of molten substance of meteoroid in conjugated (air–liquid) boundary layers on its body is applied as a mechanism of liquid particles dispersion from meteoroid surface. The numerical scheme is elaborated based on the derived differential equation for the number of breaking-away particles. Their intermediate and final distributions by sizes are calculated.

Keywords: Dispersion; gradient instability; the kinetic equation; particle distribution by sizes.

1. Introduction

The air dustiness is able to strongly influence the state of high atmosphere and the processes which proceed there. Quite a number of phenomena which occur in the high atmosphere is associated with the influx of cosmic dust, such as an increase in the intensity of the scattered solar radiation field, natural radiation and resonance scattering in lines of different atoms and ions, the mirror reflection of radio waves from a meter range of ionized meteor trails, etc. The kinetics of such processes depend strongly on the dust volume concentration and on the number distribution of the particles on sizes. In their turn, these quantities are determined by the mechanism of the process which generates these particles.

The ablation (mass loss) of moving celestial bodies is one of the origins of dust influx in high atmosphere, due to their quasi-continuous fragmentation on a large number of fine particles. There are several mechanisms of ablation being discussed in the physical theory

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of meteors: shelling, spallation, evaporation, etc. (Bronshten, 1983), one of them is breaking-off of liquid melted layer formed on the solid meteor body by the air pressure head due to hydrodynamic instability of liquid surface. The similarity in hydrodynamic conditions of meteor body (MB) to the fragmentation of liquid droplet in a speedy gas flow was revealed in (Girin, 1990). It consists in the fact that the values of Weber criterion (**We**), criterion of gradient instability (**GI**) and parameter which determines the existence of "gradient instability" mechanism, are close for the meteoroid and for drop. The performance of hydrodynamic instability of the melt film in a high-speed air flow past MB as a mechanism of particle dispersion was considered in (Girin & Kopyt, 1994) and estimations of the droplet size and frequency of the particle separation were obtained.

The results obtained in (Girin & Kopyt, 1994) are suitable for the case of overtaking ablation, when the rate of the melting penetration inside MB is not greater than the rate of MB mass efflux due to dispersion, so that the wavelength of the dominant unstable disturbance is limited by the thickness of the liquid melted film size (Fig. 1).

Certain class of middle-sized meteoroid exists (Bronshten, 1983) which are able to be melted throughout all their thickness. In this case the MB behaviour in the air is fully similar to the liquid drop behaviour behind shock waves. Thus, we can apply the elaborated recently drop atomization theory (Girin, 2014), based on the gradient instability mechanism, to the middle-sized meteoroid ablation. However, a simple expanding of the liquid drop shattering investigation in uniform flows to the conditions of the MB is incompetent due to the air density transiency caused by the altitude variability during meteoroid flight. At the same time, when the meteoroid trajectory has a slow slope the air density is changing gradually and application of the droplet dispersion theory (Girin, 2014) turns out to be feasible.

In the case of overtaking melting the molten substance thickness is greater than the thickness δ_l of the boundary layer of the melt involved in motion by the viscous stresses exerted by airstream past meteoroid. Therefore the mechanism of unstable disturbance development becomes different. The problem of the dispersion process parameters determining reduces then to the study of the hydrodynamic instability of the gradient flow in the conjugate boundary layers (Fig. 2). It was shown in (Girin, 1985) that the unstable mechanism in this case differs from the classical one of Kelvin – Helmholtz type. Its regularities are defined by the wavenumber $\Delta_\mathrm{m} \equiv 2\pi\delta_l / \lambda_\mathrm{m}$ and the growth rate factor $\mathrm{Im}(\omega_\mathrm{m})$ of the amplitude of the dominant unstable disturbance depending only on the "surface" Weber number $\mathrm{We_s} = \rho_\mathrm{g} V_\infty^2 \delta_l / \sigma$.

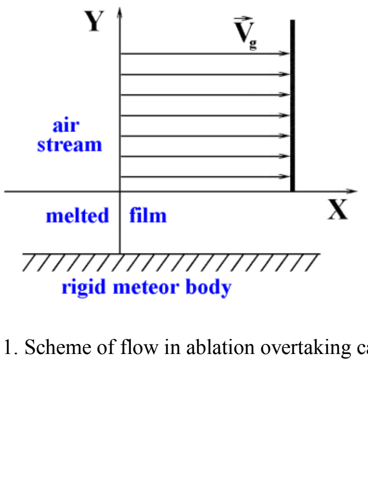

Fig. 1. Scheme of flow in ablation overtaking case.

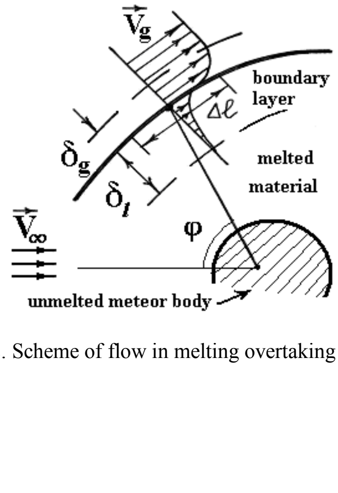

Fig. 2. Scheme of flow in melting overtaking case.

2. The dispersion mechanism

Flow around arbitrary ground Δl on MB surface is characterized by continuous velocity profile in conjugated boundary layers (Fig. 2, φ – polar angle of a ground). Boundary layers thicknesses in liquid $\delta_l(\varphi,t)$ and gas $\delta_g(\varphi,t)$ are expressed by gas flow velocity $V_g(\varphi)$ and velocity on drop surface V_s as $\delta_l = 2R_0 Q/\mathrm{Re}_l^{0.5}$ and $\delta_g = 2R_0 Q/\mathrm{Re}_g^{0.5}$, where $\mathrm{Re}_l = \rho_l V_s d_0/\mu_l$, $\mathrm{Re}_g = \rho_g(V_g - V_s)2R_0/\mu_g$ – Reynolds numbers for flows in liquid and gas boundary layers. Characteristic values of velocity gradients in boundary layers are bounded by condition of equality of viscous shear stresses at drop surface: $\mu_l V_s/\delta_l = \mu_g(V_g - V_s)/\delta_g$. By eliminating Q, we obtain:

$$V_s = (\alpha\mu)^{1/3}(1+(\alpha\mu)^{1/3})^{-1}V_g, \qquad \delta_l = (\alpha/\mu^2)^{1/3}\delta_g \tag{1}$$

where $\alpha \equiv \rho_g/\rho_l$, $\mu \equiv \mu_g/\mu_l$ are the ratios of gas and liquid densities and viscosities.

An investigation of instability of flow with continuous polygonal velocity profile had led (Girin, 1985) to the conclusion that when $\nu_l > \nu_g$ the instability is determined by classic Kelvin – Helmholtz root, since $\delta_l >> \delta_g$, $V_s << V_g$, and profile has a shape that is close to tangential discontinuity (ν is kinematic viscosity). But for the meteoroids the inverse inequality takes place: $\nu_l < \nu_g$. The unstable root ω of the characteristic equation of boundary-value problem for disturbances essentially differs in this case from that of Kelvin – Helmholtz type. It defines another type of instability – **gradient instability** (Girin, 1985), which has unstable mechanism working inside liquid boundary layer due to **huge velocity gradient** of order $(10^4 - 10^5)$ sec^{-1}.

Dominant disturbance is the most important one in applications as it may realize the particle tearing-off at the non-linear stage. Dimensionless wavenumber Δ_m and increment of dominant disturbance $\mathrm{Im}(z_m)$ depend for gradient instability only on "surface" Weber number; these dependencies are given in Fig. 3. They show that there exists critical value $\mathrm{We}_{s.cr.} = 0.004$ such that the flow is unstable when $\mathrm{We}_s > \mathrm{We}_{s.cr.}$.

Accounting for variation of flow parameters along MB surface, $\mathrm{We}_s(\varphi)$, we find that there exists a **critical point** on MB surface, $\varphi_{cr}(t)$, where $\mathrm{We}_s(\varphi)_{cr}=0.004$, which divides the surface on stable $\varphi<\varphi_{cr}$ and unstable $\varphi>\varphi_{cr}$ parts. Assuming potential flow past MB, $V_g=1.5V_\infty \sin\varphi$; and taking the boundary layer thickness distribution along MB

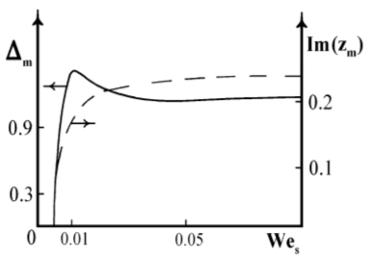

Fig. 3. Dependencies $\Delta_m(\mathrm{We}_s)$ and $\mathrm{Im}(z_m(\mathrm{We}_s))$.

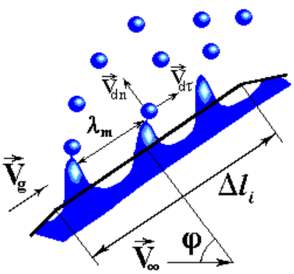

Fig. 4. Dispersion at elementary ground.

surface in Ranger's form (Ranger, 1972):

$$\delta_g(\varphi,t)=2.2R(t)\mathrm{Re}^{-0.5}(t)\Psi(\varphi)\,,\;\; \Psi(\varphi)\equiv((6\varphi-4\sin 2\varphi+0.5\sin 4\varphi)/\sin^5\varphi)^{0.5}$$

we find the condition for the gradient instability existing on MB surface:

$$\frac{2.475}{\left(1+(\alpha\mu)^{1/3}\right)^2}\sqrt{\tilde{R}(\tau)\left(1-W(\tau)\right)^3}\,\sin^2\varphi\,\Psi(\varphi)\,\mathrm{GI}\geq 3.08 \qquad (2)$$

here $\mathrm{GI}\equiv \mathrm{We}_\infty/\mathrm{Re}_\infty^{0.5}$ is gradient instability criterion (Girin, 1985), $\tilde{R}=R/R_0$, $W=w/V_\infty$ are dimensionless MB radius and velocity, R_0 – initial MB radius, $\tau=t/t_{\mathrm{ch}}$, $t_{\mathrm{ch}}=2R_0/\sqrt{\alpha}V_\infty$ – characteristic time scale, V_∞ – gas flow velocity. Equality in (1) defines the value of φ_{cr}; at $\mathrm{GI}>0.4$ we have $\varphi_{\mathrm{cr}}<\pi/2$. This means, that the **part of MB surface adjacent to edge is unstable, providing a possibility of dispersing**. The values of φ_{cr} are small enough, $\varphi_{\mathrm{cr}}\ll\pi$, when $\mathrm{GI}\gg 0.4$, so, the most part of MB surface generates a mist of droplets (Fig. 4). The condition $\mathrm{GI}>0.4$ was grounded theoretically in (Girin, 1985) as criterion of the gradient instability existing on a drop surface.

The magnitude of We_s is variable along the MB surface changing with φ (Fig. 2). It also varies in time due to the meteoroid deceleration, so, Δ_m and $\mathrm{Im}^{-1}(z_m)$ are dependent on φ and t. Similar to routine scheme for the case of a drop in gas stream (Girin, 2014), the MB surface are divided in present paper onto the system of elementary grounds (spherical belts) of width $\Delta l=R(t)\Delta\varphi$ and values $V_g,\delta_g,\delta_l,\mathrm{We}_s,\Delta_m,\mathrm{Im}(z_m),\; r,t_i$ are computed on each ground at each time step. When the part of induction time of the disturbance growth exceeds unity, it is supposed that the separation of droplets of number $\Delta n\approx\Delta l\cdot\Delta_m$ and radius r occurred that moment from the corresponding ground. It is assumed that droplet sizes and period of their tearing-off are proportional to values $\Delta_m(\varphi)$ and $\mathrm{Im}(z_m(\varphi))$: $r=k_r\Delta_m^{-1}$, $t_i=k_t\,\mathrm{Im}^{-1}(z_m)$, In such a way we obtain the equations for the droplets quantity and radius (Girin, 2011):

$$\dot{n}'(\varphi,\tau)=B_1^3B_2\tilde{r}^{-3}\tilde{R}^2(\tau)(1-W(\tau))\sin^2\varphi,\quad \tilde{r}(\varphi,\tau)=B_1\sqrt{\tilde{R}(\tau)/(1-W(\tau))}\,\Psi(\varphi)\,, \qquad (3)$$

where $B_1=\dfrac{4.4\pi k_r\alpha^{1/3}}{\Delta_m\mu^{2/3}(2\mathrm{Re}_\infty)^{0.5}}$ and $B_2=\dfrac{0.21\Delta_m^2\,\mathrm{Im}(z_m)\mu^{7/3}(2\mathrm{Re}_\infty^3)^{0.5}}{\pi k_r k_t\alpha^{7/6}(1+(\alpha\mu)^{1/3})}$ have the sense of scaling parameters for the particle sizes and quantity, respectively, dot stands for differentiation with respect to τ, and asterisk – to φ.

3. Results and discussion

Quantitative description of heat and mass transfer in a meteor wake is important in the physical theory of meteors (Bronshten, 1983). Mathematical modeling of the meteor wake structure requires finding the distribution of all torn-off particles by sizes, as well as of its evolution in space and time. The distributions of stripped droplets by sizes are calculated in accordance with eqn. (3) and results are given in figs. 5-7. Meteor velocity during the flight was assumed to change in accordance with empirical law $W=1-\exp(-C\tau)$, parameter C =

$2\alpha^{0.5}$ has the sense of MB deceleration (Girin, 2011). Calculated dependence of MB radius on time is close to linear.

Calculations yield quite a large number of particles for the speedy iron meteors, which are two orders less by sizes than the parent meteoroid. The coarse fraction is generated always at the beginning, and the fine one – at the end of the process when the MB radius is small. With MB velocity diminishing the particle sizes increase as $V_\infty^{-0.5}$ while their number decreases.

Bimodal meteor particle distribution may exist due to the "hump" in Δ_m (We_s) dependence in Fig. 3. Near the critical point φ_{cr} on MB surface the "hump" influence causes shifting of the particle sizes toward the decreasing.

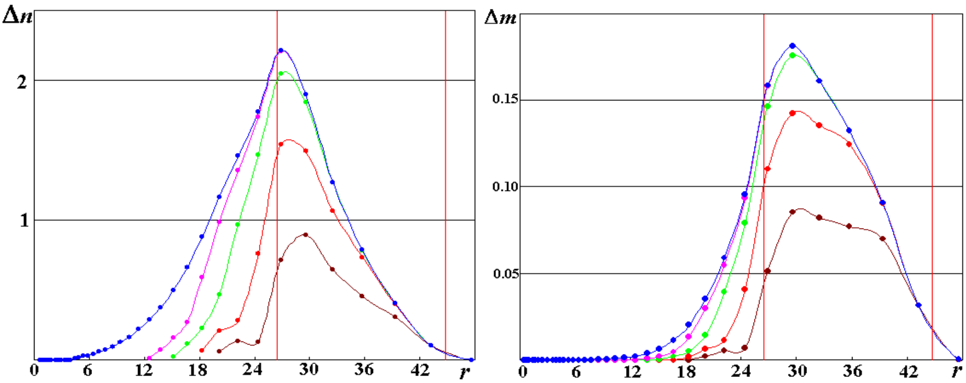

Fig. 5. Distributions of stripped droplets by sizes: $\Delta n(r)\cdot 10^4$ (left) and $\Delta m(r)$ (right); r in μm. **Iron meteor**, V_∞= 60 km/sec, R_0 = 3.0 mm, Re_∞= 529; GI = 13.0. Blue – final distribution at τ = 2.72; brown, red, green, crimson – intermediate distributions at τ = 0.44, τ = 0.89, τ = 1.39, τ = 1.80; τ_{ch} = $2.16\cdot 10^{-3}$ sec.

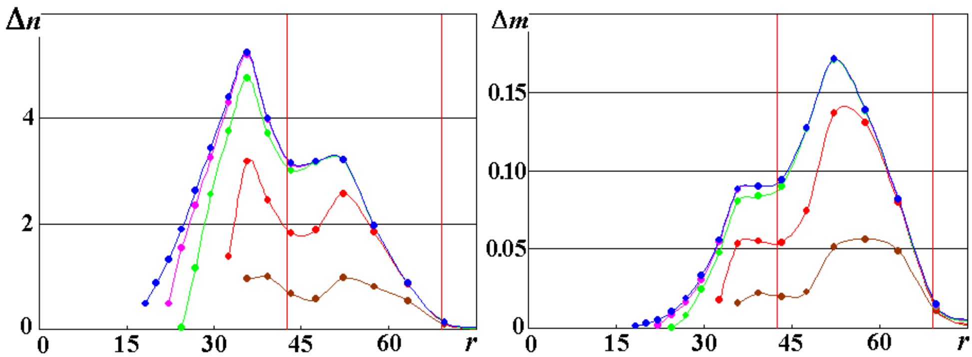

Fig. 6. Distributions of stripped droplets by sizes: $\Delta n(r)\cdot 10^4$ (left) and $\Delta m(r)$ (right); r in μm. **Iron meteor**, V_∞= 25 km/sec, R_0 = 3.0 mm, Re_∞= 222; GI = 3.55. Blue – final distribution at τ = 3.11; brown, red, green, crimson – intermediate distributions at τ = 0.30, τ = 0.93, τ = 1.88, τ = 2.48; τ_{ch} = $5.15\cdot 10^{-3}$ sec

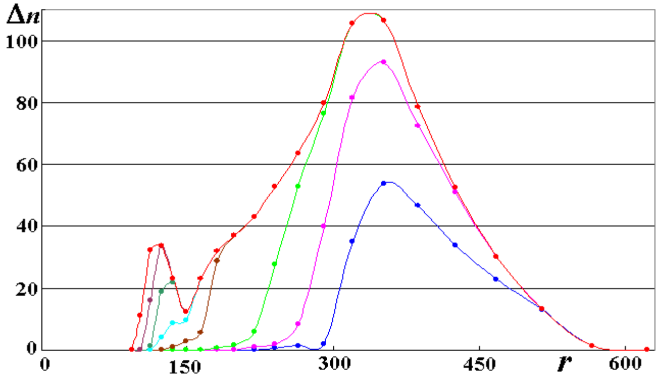

Fig. 7. Distributions of stripped droplets by sizes; r in μm. **Stony meteor**. V_∞= 60 km/sec, R_0 = 3.0 mm, Re_∞= 529; GI = 43.5. Red – final distribution at τ = 103; blue, crimson, light-green, brown, light-blue, green, dark-brown – intermediate ones at τ = 2.05, τ = 3.88, τ = 5.94, τ = 9.96, τ = 16.8, τ = 29.9, τ = 48.7; τ_{ch} = 1.45·10^{-3} sec.

At smaller GI values this effect becomes more distinct, as Fig. 6 shows. The "hump" can also be in work in the case of the more viscous meteor body substance. In Fig. 7 one can see the distribution of particles in the case of stone meteoroid, whose viscosity is 30 times greater than the iron one has. In this case the boundary layer thickness δ_l is only 6 times less than meteoroid diameter, so, the particle sizes are larger and their number is lesser.

4. Conclusions

The presented model of the melted meteor body ablation, which is based on the gradient instability mechanism, provides elementary theory of the meteoroid atomization for the case of slow-sloped trajectory.

The ablation law and the transient distribution of particles, which are torn-off to the current moment, are obtained at some simple assumptions.

The model makes it possible to describe quantitatively further aerodynamics of the totality of accelerating and evaporating mist of stripped particles, which comprise the meteor wake.

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