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THE FORMATION AND DISSIPATION OF A METEOR COMA

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Abstract. The results of reduction of instantaneous fireball photographs are presented. The observational data testify to the fact that linear dimensions of the region radiating after the meteor's flight amount to tens and hundreds of meters, and in the case of particularly bright fireballs to some kilometers. The suggested by authors hypothesis of synchronous length change of the region of fireball afterglow alongside with its light variation is verified. The analysis of the spectral photograph obtained by authors with the method of instantaneous exposure shows that the afterglow proceeds mainly to radiation in H and K lines of CaII. Several mechanisms of ionized atoms afterglow of the meteor substance are discussed. Photometric profiles of the instantaneous images of meteors are compared with theoretical calculations made both on the supposition of the parent body fragmentation and on that of afterglow of ionized atoms of meteor substance. The conclusion on a joint effect of both above-mentioned mechanisms is obtained.

Key words: instantaneous meteor photograph, the luminosity of fragments ejected from parent body, afterglow of meteor plasma.

Penetrating into the dense atmosphere layers, a meteor body reaches the temperature of melting. During a meteor body flight, the small particles and the melted droplets break away from its surface. At the same time, the evaporation of meteor substance takes place both from the surface of a meteor body itself, and from those of particles and droplets - a luminous region (a meteor coma) is forming around the meteor body.

The evaporated meteor atoms lose their cosmic velocities during a few collisions, and in 10^{-4} - 10^{-5} s they are not capable to excite themselves and to radiate (Opik, 1950). Hence, if the meteor luminosity is caused by the evaporated atoms only, the dimensions of the luminous region would not exceed a few free path lengths - about few meters (Babadzanov and Kramer, 1965) and the meteor image would be practically a dotty-like.

But as far back as the fifties, McCrosky (1955,1958), Jacchia (1955), Halliday (1958), Hawkins and Southworth (1958) discovered the large dimensions of meteor luminous regions, by analyzing the blending of shutter breaks on meteor images. As instantaneous photographs of the bright meteors have shown, the length of the luminous meteor coma amounts to tens and hundreds of meters, and, in case of fireballs - to some kilometers. In addition, the instantaneous images of bright meteors have comet-like forms: the bright head part of an image turns gradually into the tail, and extends along the meteor body trajectory.

The meteor coma extension may be caused either by a lag of the ejecting fragments from a parent body (PB) or by an afterglow of the meteor atoms and ions that lose their cosmic velocities almost completely. In the first case, the ejected fragments decelerate, lag behind the PB and continue to evaporate, and the evaporated meteor substance is shining behind the PB (Levin, 1961,1963; Jacchia et al., 1965; Levin and Simonenko, 1966,1967; Simonenko, 1967,1969,1973a,1973b, 1974; Lebedinets and Portniagin, 1967; Musij and Shestaka 1968; Novoselova 1971).

In the second case, the meteor atoms and ions, which remained behind the PB, decelerate to the thermal velocities at the given height. Then they have not enough kinetic energy for the collision excitations and luminescence. But they are able to shine due to the exchange excitations or recombinations. In this case, the head part of a meteor can go far ahead a nearly motionless luminous coma. Thus the dimensions of the latter must change synchronously with the brightness of the meteor itself.

The luminescence of a meteor coma as a result of a quasicontinuous separation from a PB of a large number of the fragments (the first mechanism) was discovered both at ordinary meteor photographs (Ceplecha, 1953;Kramer, 1960,1967,1968a) and at the instantaneous ones (Babadzanov and Kramer, 1967b,1968; Kramer et al.1976,1979).

Nevertheless, there are many facts, which cannot be explained by the disintegration of the PB only. These are dependence on wakes' lengths on meteor brightness, the synchronous changes of wakes' lengths with meteor brightness and meteor flares too, the observational dimensions of wakes. We give, as an example, the analysis of the instantaneous images (IIs) of the fireball, which was photographed on August 13, 1974.

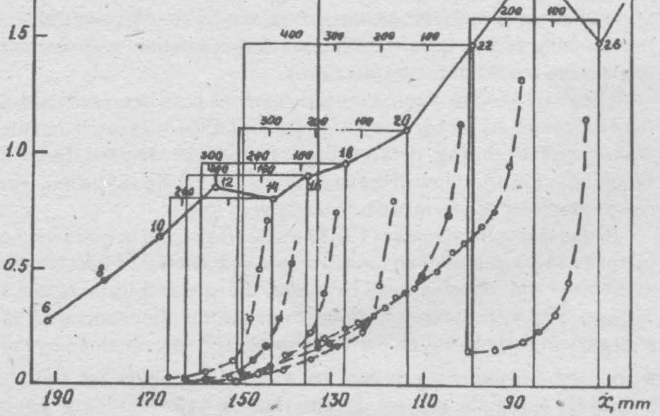

Fig. 1 The photometric profiles of instantaneous images of the fireball photographed on August 13, 1974.

The photometric profiles of the IIs of the 1974.08.13 fireball are given in Fig. 1, where x is a measured distance of any point of the meteor image from its disappearance point, D is a corresponding photographic blackening. The solid line represents the D-changes of the head part of instantaneous images (Figures 6 to 26, at empty circles there are numbers of corresponding IIs) and the dashed lines represent the in situ distances (s) of some points of images (Ns 14 to 26) from the head of the corresponding image (the distance scale in meters is shown by means of horizontal lines which come from the corresponding image number).

Figure 1 displays the obvious wakes' lengths vs the meteor brightness. It is seen clearly on the IIs of Ns 24 and 26, which are obtained during the flare and the depression of the brightness, respectively: the wake length is decreasing drastically when the meteor brightness is declining too.

We must note a complicated character of the intensity of wakes' images. Thus the intensities of the 25th, 26th, 28th, 29th, 31th and 32th images at first are decreasing, then they are increasing on and decreasing on again. All the above said does not go into frameworks of hypothesis of forming and luminescence of a meteor coma due to quasicontinuous fragmentation of the PB only.

For the verification purpose, we carried out the theoretical calculations of photometric profiles of IIs of meteor body, assuming that it underwent the quasicontinuous fragmentation. We used the following initial data: the mass of the PB $M_0 = 1$ g, its velocity $v_0 = 60$ km/s, the zenith distance of the radiant $Z_R = 0^\circ$, the mass of the fragment at the moment of its separation from the PB $m_0 = 10^{-6}$ g, its velocity at the same time $v_0 = 60$ km/s too, the density of the meteor substance $\delta = 5.3$ g/cm^3, the atmosphere density at the height h_m of the maximum brightness of the unsplitting meteor body $\rho^* = 1.2\ 10^{-9}$ g/cm^3, the moment of the maximum brightness of the unsplitting PB $t_m = 0$ s, the height of the standard atmosphere $H^* = 6.0$ km, the shape parameter $A = 0.4134$, the drag and heat-transfer coefficient $\Gamma = 1$ and $\Lambda = 1$, heat of ablation $Q = 8 \cdot 10^{10}$ erg/g. The step of the numerical integration $\Delta t = 5 \cdot 10^{-3}$, $2.5 \cdot 10^{-3}$, $1 \cdot 10^{-3}$ s. All calculations were carried out for heights

$$h_i = h_m - v_0 t_i \cos Z_R$$

under the assumption, that the expression for the intensity of the PB fragmentation takes the form

$$\frac{N_i}{N_m} = \frac{9}{4} \exp\left(\frac{h_m - h_i}{H^*}\right) \left[1 - \frac{1}{3} \exp\left(\frac{h_m - h_i}{H^*}\right)\right]^2 ,$$

where N_i and N_m - are the numbers of particles ejected from the PB per second at heights h_i and h_m, respectively, $i = 1,2,\ldots,n$. The modelling was carried out according to two algorithms. The first of them doesn't take into account the fragments' energy lost on the evaporation and radiation, the second algorithm does take into consideration these losses.

A variable t_i corresponding to a fragment height h_i is used as an independent variable (a sign of t_i agrees with that of a difference $h_m - h_i$). The calculations of the drags, ablations, intensities and lags of the fragments from the PB are carried out according to such a scheme (Kramer and Shestaka, 1979)

$$\rho_i = \frac{\rho^* v_0}{H^*} \cdot \cos Z_R ,$$

$$\Delta v_i = \Gamma A m_i^{1/3} \rho_i v_i^2 \Delta t , \qquad v_i = v_{i-1} - \Delta v_i ,$$

$$\Delta m_i = \Lambda A m_i^{2/3} \rho_i v_i^3 \Delta t/(2Q) , \qquad m_i = m_{i-1} - \Delta m_i ,$$

$$I_i = \frac{\tau_0}{2 \Delta t} \Delta m_i v_i^3 , \qquad S_i = S_{i-1} + 0.5 (v_{i-1} + v_i) \Delta t$$

$$S_i = i \cdot v_i \Delta t - S_i , \qquad i = 1, 3, \ldots, n.$$

The comparison of the changes of the wake length s at the given moment (the dashed line) and of the relative intensity I_i / I_m (the solid line) is shown at Fig. 2. It is distinctly seen, that a wake length begins to decrease long before (0.1 s) the point of the maximum brightness. Moreover, the theoretical wake length (100 m) is less than the observed one. The similar procedure occurs in the case of the variations of initial masses and velocities of the PB, initial masses of fragments, beginning heights of the fragmentation of the PB etc.

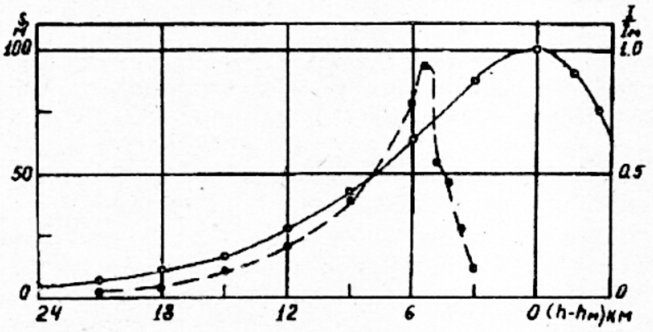

Fig. 2 The linear dimension (s) of an 'instantaneous' image and the relative luminosity (I/I) of a standard meteor (the results of modelling).

The estimation of the heat radiation of the fragments and their energy expenses for evaporation does not eliminate these contradictions either. Hence, the natural conclusion follows that the mechanism of the quasi-continuous fragmentation only cannot explain the results of the observations.

The search for the alternative mechanisms have been carried out for a long time. As far back as 1950, Opik (1950) suggested that the wakes and blending of shutter breaks had resulted from a recombination afterglow of the meteor matter, but he supposed, that the productivity of this mechanism was very low.

Babadzanov and Kramer (1965) made an attempt to evaluate the intensity and duration of an ion afterglow and obtained a satisfactory agreement with observations. However, the spectral instantaneous photographs were lacking in order to reveal the mechanism of an afterglow in meteor wakes. Such a photograph was obtained by the authors of this paper on August 13, 1974. Its analysis has shown, that the luminescence in the fireball wake occurs through H and K lines Ca II mainly. It is significant, that the wakes' luminescence takes place behind this duplicate only. This duplicate luminescence in the wakes of the photographic meteors was noted by other scientists too (Raichl, 1964; Bronshten and Lubarsky, 1966; Ceplecha, 1971; Harvey, 1971).

Thus the conclusion is forced upon, that the meteor ions' afterglow and the luminescence of the PB fragments separated in the process of quasi-continuous fragmentation are capable to explain the observed variety of photometric meteor profiles. But in this case, it is necessary to reveal the mechanism of the ionized atoms' origin in a meteor coma. Two suggestions are possible:

1) a forming of ionized atoms of Ca and other elements of meteor substance takes place in a fast meteors' coma itself,

2) the twice ionized atoms of Ca are forming in a meteor coma due to a very large energy of the fast meteors' collisions with the dense layers of the atmosphere, then the duplicate H and K Ca II is emitting as a result of the radiative recombination of the twice the ionized atoms of Ca.

In the first case, some processes can result in the calcium ions' excitations. Firstly, it is an excitation caused by an electron impact

$$Ca^{+} + e \rightarrow Ca^{+*} + e \ .$$

At second, it is a transmission of an excitation to calcium ions by the air atoms (molecules) or ions

$$Ca^{+} + A \rightarrow Ca^{+*} + A \ ,$$

$$Ca^{+} + A^{-} \rightarrow Ca^{+*} + A + e \ ,$$

$$Ca^{+} + A^{+} \rightarrow Ca^{+*} + A \ .$$

A third, it is a change of the charge due to the excitation

$$Ca^{+} + A^{+*} \rightarrow Ca^{+*} + A \ .$$

Here A is a neutral atom (molecule) of air, A^{+} , A^{-} - are the air ions and e is an electron. The index (*) indicates the state of the excitation.

Since the luminosity intensity of the excited calcium ions is directly proportional to their numbers that decrease according to the exponential law due to the recombinations, the afterglow intensity of the meteor coma obeys the same law. According to the second suggestion, the luminosity intensity of a meteor coma is directly proportional to the numbers of Ca III ions recombinating per second. The corresponding reaction can be described by means of the following system of the differential equations

$$\begin{cases} \dfrac{\partial n_j}{\partial t} = -\mathrm{D}_a \cdot \Delta n_j - p_j n_j n_e \ , \\ \dfrac{\partial n_e}{\partial t} = -\mathrm{D}_a \cdot \Delta n_e - p_e n_e^2 \ , \end{cases}$$

where n_j , n_e - are number densities (concentrations) of Ca II ions and electrons, respectively, D_a - is the coefficient of the ambipolar diffusion, p_j - is the coefficient of the radiative recombination, and p_e -is the adhesion coefficient. Integrating this system over the cross-section of the ionized column, and passing over to linear concentrations, one may obtain the expression for the intensity of radiation:

$$J(t) = \tau_j \frac{\partial \alpha_j}{\partial t} = \frac{\tau_j p_j \alpha_i^{(0)} \alpha_e^{(0)}}{2\pi r_0^2 \left(1+\dfrac{4\mathrm{D}_a t}{r_0^2}\right)\left[1+\dfrac{P_e \alpha_e^{(0)}}{8\pi \mathrm{D}_a}\cdot \ln\left(1+\dfrac{4\mathrm{D}_a t}{r_0^2}\right)\right]^{1+pj/pe}} \ ,$$

where τ_j - is the coefficient of the luminous efficiency of Ca II ions, α_j and α_e - are the linear concentrations of Ca III ions and the negative ions, respectively, r_o - is an initial radius of the meteor- ionized column (Kashcheev et al., 1967). The index (o) corresponds to the values of α_j and α_e at $t=0$.

Suggesting, that the linear concentration of electrons is not changing during the afterglow and remains equal to N, the last equation turns into the following expression

$$J(t) = \tau_j p_j N \alpha_j^{(0)} \exp(-p_j N t) \ .$$

If t=0, i.e. in the head part of meteor

$$J(0) = \tau_j p_j N \alpha_j^{(0)}$$

Hence, it follows

$$\frac{J(t)}{J(0)} = \exp(-p_j N t) \ .$$

We calculated the value of $p_j N$, by using the two points of the photometric profile of the wake obtained from the observations. It proved to be equal to $2.5 \cdot 10^{2}$ cm^2/s. In case of atomic ions, the radiative recombination coefficient is equal to $p_j \sim 10^{-12}$ cm^3/s (Kashcheev et al., 1967), hence, the linear concentration of the negative ions $N = 2.5 \cdot 10^{14}$ electrons/cm. In fact, this value is larger (Kashcheev et al.,1967). The above-mentioned value of $p_j N$ was used for the calculations of the theoretical decrease of the afterglow

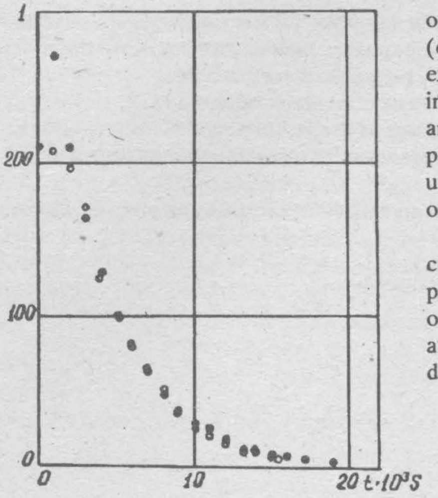

Fig. 3 The observational (dots) and theoretical (open circles) luminosities of the afterglow in the meteor tail.

of a meteor coma. As one may see at Fig. 3, the theoretical (open circles) and measured (dark circles) intensities of the wake luminosity coincide satisfactory. There is the intensity excess observed above that of the theoretical one in the head part of an instantaneous image only. This can be explained easily because, at first, in a head part of a meteor image an effect of the photographic diffusion is not taken into account (this doesn't affect the tail part of a meteor image) and, at second, the calculation of the afterglow was carried out under the assumption, that the luminosity of the meteor coma had resulted from radiation of H and K Ca II only.

The real meteor phenomena are complicated to a far greater extent than the models considered in this paper. The thorough investigation of the instantaneous meteor photographs argues, that, simultaneously with a parent body fragmentation, an evaporation of meteor particles, the collision excitations and the radiation of the evaporated meteor atoms, there is the afterglow of the excited atoms and ions, and also the lighting of smallest dust particles by radiation of the meteor head part.

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