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Formation of disturbed area around fast meteor body

By

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Abstract: The detailed observations that occurred during the recent Leonid showers/storm have provided a wealth of data on fast meteors, with an entry velocity of 72 km/s and wide range of meteor sizes. Despite many attempts, the details of the interaction between the entering particles and the atmosphere are still poorly understood. We propose a physical model of high-velocity, high-altitude meteors taking into account their ablation and radiation. A new approach is used to calculate this model that includes both gasdynamical and statistical simulations. This combined description allows us to take into account all features of the considered process - meteoroid motion in rarefied flow at high altitudes and formation of a vapor cloud around the body, to consider nonelasitic processes in particle collisions and to determine the resultant luminous area.

1. INTRODUCTION

Classic approach to meteor interaction with atmosphere consists of two limiting cases. Large meteoroid at relatively low altitude (shock wave is formed) is satisfactory described by hydrodynamics models. Small meteoroid and/or high altitudes are considered in the frame of free molecule flow. Collisions between evaporated meteoroid particles usually are not taken into account. This approach (first collisions) describes rapid expansion and formation of initial train radius (Jones 1995). That doesn't contradict in general to radiometeor observations. But interaction of cm-sized Leonids and other fast meteors with atmosphere cannot be described by both approaches. Recently new evidences (nebulous meteors, jet-like features) were obtained and still have not explained. It was speculated that this unexpected structuring are caused by explosive ejection of meteoroid fragments (Taylor et al. 2000). But the nature of such explosions is not yet known. High altitude radiation and diffuse structure above 130 km altitude also can't be described by classical ablation theory.

To better understand observational data on fast meteoroids one needs to have clear description of the meteoroid-air-vapor interaction. No such complete picture of this interaction

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currently exists. High velocity meteor interaction with atmosphere differs substantially from entries of artificial bodies due to ~10 fold excess of entry velocity and meteoroid properties (composition, strength). The high velocity of fast meteors results in high-altitude beginning of intensive evaporation (110-130 km) and also provides high evaporation rate. Pressure of formed vapor is higher than aerodynamical loading. That results in formation of vapor cloud around the body and vapor cloud screening. The most part of fast enough bright (brighter about + 3 mag) visual meteors interacts with atmosphere in transition regime from a free-molecule flow to a continuos one (Popova et al. 2000, 2001).

2. AIR BEAM MODEL

The energy transfer during the penetration of air into the layer of evaporated molecules may be described similar to radiation transfer assuming some effective mass absorption coefficient (Popova et al. 2000). In that case vapor can be described gasdynamically, whereas air as particle beam. It was demonstrated earlier that the self-regulating regime is realised (Nemtchinov et al. 1967; Popova et al. 2000, 2001). We also confirm this by 2D modeling.

According to beam model it was assumed that the particles energy is absorbed both by vapor causing its heating and expansion and by meteoroid itself causing its evaporation. The 1 cm in radius body at 100 km altitude was considered. It was assumed that air energy, momentum and mass fluxes are absorbed with the same absorption coefficient (Fig.1). Hydrodynamical description allows to take into account evaporation, air loading and mass stripping. Radiation is not taken into account in these simulations. Modeling shows that vapor cloud is formed

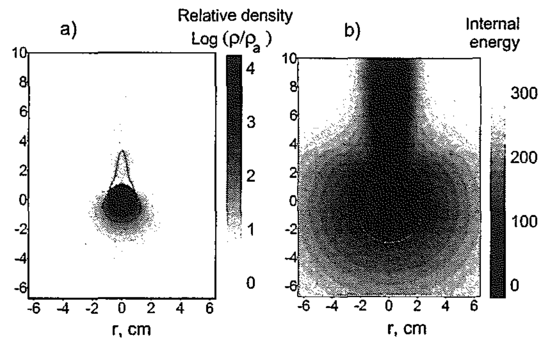

Fig. 1: Distribution of relative density (a) and dimensionless internal energy (b) around a 1 cm body at 100 km altitude

around the body. Gasdynamic cannot be applied to nonablating body, but it may be used for ablating one. Total size of dense vapor cloud is about 5-10 body size. More detail description can be found in Popova et al. (2000, 20001).

The 2D modeling was used as a foundation to modify 1D simulations, to refine details of energy, momentum and mass transfer processes. We include EOS of cometary substance (Kosarev et al. 1996) and radiation transfer into our 1D simulations in order to determine vapor parameters. Vapor parameters depend on meteoroid size, velocity, altitude of flight and composition. Near the meteoroid surface vapor has the lowest temperature (Fig.2), close to the evaporation one. Vapor temperature increases with body size R (more evidently before radiation influence) and with velocity V (in accordance with high temperature vapor spectral component behaviour (Borovička et al. 1994). Vapor temperature also increases with altitude decrease, so spectra should be altitude dependent (agrees with observations by Abe et al. (2000)). Density of vapor is about 10^{-6} g/cm^3 - 10^{-9} g/cm^3 and rapidly decreases with distance from the body. It also decreases with body size until radiation influence (Fig.2).

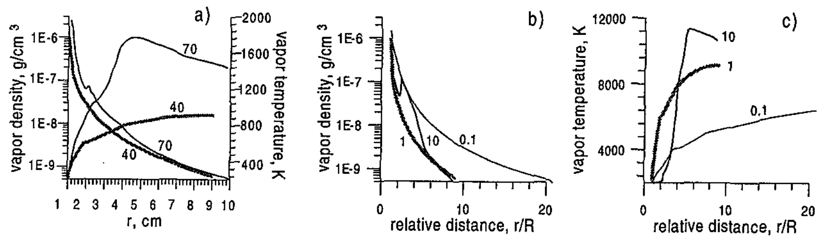

Fig. 2: Dependence of vapor cloud parameters at 100 km altitude (a) on velocity V (40 km/s and 70 km/s, given at the curves, R=1 cm); (b,c) on meteoroid size R (0.1, 1 and 10 cm, marked at the curves, V=40 km/s).

It was shown earlier (Popova et al. 2000) that the radiation should be included into account below some altitude of flight. The radiation decreases maximal temperature, at low altitudes it also results in density and cloud size increase. Reradiation of vapor may be substantial in formation of vapor cloud.

The unclear question is the precise value of the energy deposition length. Model of mass and momentum deposition allows to estimate mixing of air and vapor but also should be verified.

3. MONTE CARLO MODELING

To be certain that the air energy absorption is well described by the air beam model we consider the energy transfer from air flow to meteor body and vapor cloud around it with Monte Carlo (MC) type calculations. In meteor studies particle dynamics was considered in estimates of initial train radius and ionization coefficient for small meteoroids (Jones 1995,1997), in attempt to explain head echo formation (Jones et al. 1999). These considerations relate to relatively small and/or low velocity bodies where screening effect is insignificant and no interaction of ablated atoms with each other was considered.

Recently, the MC approach was used to describe the rarefied flow around a Leonid meteoroid with a simplified ablation model (Boyd 2000) and have demonstrated the critical influence of ablation on formation of long hot meteor wake. The size of hot meteor wake essentially increases if the ablation is taken into account.

We simulated the energy transfer from air flow to meteor body, concentrating on the ablation process itself and the vapor cloud surrounding the meteoroid. Our model is a 2D MC calculation of the action of impinging air molecules from one direction on a spherical vapor cloud with densities from 10^{-11} to 10^{-5} g/cm^3. The particle trajectories are simulated in a volume consisting of the meteoroid body with radius R=1 cm and a developed vapor cloud. We assume here pure silicium meteor body. More detail may be found in Popova et al. (2000).

As the first approximation the interaction of the impacting air particles with the meteoroid and vapor cloud is considered as paired elastic collisions. The initial kinetic energy of high velocity air molecules is much larger than the thermal energy of the vapor. The simulation process involves the construction of a trajectory for the impacting air particle and several generations of fast vapor particles. Absorption implies the decrease of particle kinetic energy to the value less than some threshold (0.1-0.5 eV) (Fig.3a). The density distribution in the

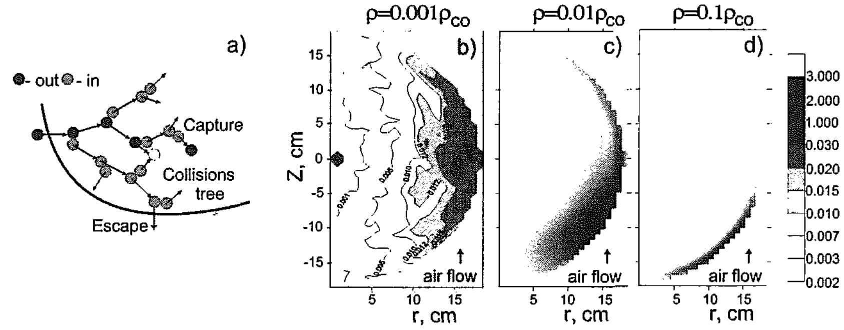

Fig. 3: a) schematic picture of particles trajectories; (b, c, d) absorbed energy spatial distribution in vapor cloud (ρ_{co}=10^{-5} g/cm^3)

vapor cloud is assumed to be almost uniform with constant density value in order to understand better the collision processes. The energy distribution change with vapor density is presented on Fig.3(b-d). Density contours show the transferred energy. At low densities the energy absorption takes place in the whole volume of the vapor cloud and body itself. As the vapor cloud density increases, the region of highest energy absorption shifts to the volume boundary and becomes a thin layer located on the frontal surface of the cloud. At high vapor densities, all energy absorption occurs in the cloud.

The energy deposition length is larger than the scattering length. The size of initial particle influence area is larger than the initial particle by an order of magnitude. So, it may be assumed that energy deposition length is equal to 10 free path lengths of air particles in the vapor.

Air particles with initially oriented velocity vector enter into evaporated meteor substance. The average angle of scattering is about $\pi/4$, the oriented motion becomes isotropical after about 2-3 collisions. Energy decreases continuously. This process is similar to neutron propagation in the air which is well describes by the 'age theory' (Jampolskij 1961). In that case square of absorption distance r_{age}

$$\overline{r_{age}^2} = 6\int_E^{E_0} \frac{\ell_t \cdot \ell_s}{3\xi} \cdot \frac{dE}{E},$$

where ℓ_s - scatter length; $\ell_t = \frac{\ell_s}{1-\overline{cos\psi}}$; $\overline{cos\psi} = 2/3$, and average losses $\xi = ln\left(\frac{E_n}{E_{n+1}}\right) \sim 2/3$.

Setting the absorption energy E_{end} to be equal 0.25 eV, initial energy $E_0\sim$ 340 eV, we obtain the energy deposition length r_{age} to be about 8 scattering length ($r_{age}\sim 8\ell_s$). That is close to our modeling.

We also consider what is the fate of impinging air particles (Fig.4a). The fractions of air atoms that escape from the head cloud into wake and remain in the head with thermal velocity are shown. The fraction of remained particles increases with relative density from few % to about 70%. The number of escaped meteor particles per one air molecule also is given (Fig.4b). In relatively dense cloud one air molecule causes about 20-70 meteor particles to be thrown into meteor wake. It should be remembered here that one initial air molecule could cause appearance of about 200 vapor particles. And some balance, some quasistationar picture is established.

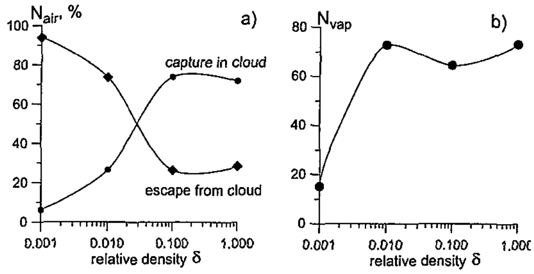

Fig. 4: a) fraction of air atoms captured by vapor cloud and escaped from it b) number of vapor particles escaped from meteor head per one air molecule ($\delta=\rho/\rho_{co}$, $\rho_{c0}=10^{-5}$ g/cm^3)

It is important to know what is the real energy, momentum and mass deposition length because it governs the established thermodynamical parameters in the vapor. We see the following steps that should be done. First, we need to consider the interaction of air particles with more real composition of vapor. We begin with determination of the energy deposition length considering the primary and secondary scattering. We need to improve model of momentum transfer and to take it into account in gasdynamic simulations more precisely. Second, we need to include non-elastic processes. The equilibrium part of non-elastic processes is taken into account during the gasdynamical description of the vapor. The nonequilibrium part (ionization by hard particles) may be included in MC type simulations.

We considered composition close to H-chondritic one and estimated ionization cross-sections for different elements in their collisions with air particles (following (Kuns & Soon 1991)). Examples of cross sections for elastic and ionizing collisions are given on Fig.5. Cross-section

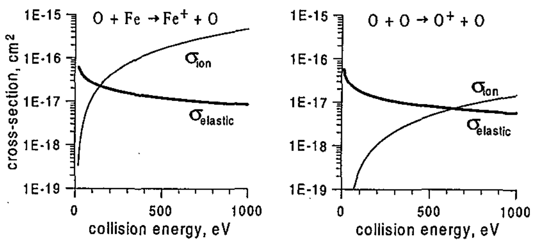

Fig. 5: Comparison of elastic and hard particle ionization cross sections

for ionization is larger than elastic one for high energy of colliding particles.

We found that the cross sections of vapor particle ionization ($\sigma_{ion}\left(A+M\rightarrow A+M^{+}\right)$) is larger than that of air particle ($\sigma_{ion}\left(M+A\rightarrow A^{+}+M\right)$). Here M is vapor particle and A is air particle (N_2, O_2, O, N). Thus we should expect that the most part of ions will be vapor ions.

Then we estimate the fraction of ionizing collisions in total collisions $\delta_i=\sigma_i/\left(\sigma_i^{elastic}+\sigma_i^{ion}\right)$. The main addition into equilibrium ionization may be expected from ionization of Fe, O, Mg, Si. It should be mentioned here that in the case of relatively big and fast meteor bodies coefficients of ionization and excitation should be calculated taking into account both collisions with air particles and with vapor particles due to enough large number of collisions in the meteor head and vapor cloud. The observations show that LTE is in rough agreement with meteor radiation

(Borovička et al. 1999). That also proves the necessity of total collisions consideration.

4. THE METEOR WAKE AND SHAPE OF LUMINOUS VOLUME

Total luminous area of meteor includes both head and wake. The precise boundary between the head and the wake, as well as a shape of the luminous volume, is not well known. Recent MC simulations by (Boyd 2000), demonstrated the formation of a large (10–40 m in length) wake with temperature of about 5,000-10,000K. And this identifies the wake as the source of the temperature measured from atmospheric line and band emission of Leonid meteors in the 1998 Leonid MAC (Jenniskens et al. 2000). Estimate of the wake parameters near the meteoroid itself were done in the frame of our air beam model (Popova et al. 2000) and have shown that the extended hot area far exceeds the meteoroid size itself. Our estimate agrees with results by Boyd (2000).

Theoretical predictions provide disturbed area about meters width and tens (and more) meters length. What is known from observations about meteor luminous volume? The custom video observations are mainly integrated over large exposition time ($\tau \sim$ 33 ms) that corresponds to meteoroid path about 2 km along trajectory (for Leonid meteors).

Up to now there are extremely scarce observations with short exposition time τ. A number of meteors was recorded by Babadzhanov and Kramer (1968) with $\tau \sim 6 \cdot 10^{-4}$ s. They found different types of images (from "dotted" images to distinctly visible disc and a long tail). Fast meteors mainly reveal head and tail with the average length about 50-150 m (up to 400 m). Meteor tails also were investigated by Fisher et al. (2000) (with $\tau \sim 4 \cdot 10^{-4}$ s). They analysed 9 sporadic meteors. Four meteors had statistically significant wake (about 50-100 m). There are no data on meteor velocities. Few meteors revealed also transverse separation (or nebulous structure). One of them (max brightness -4^{mag}) had lateral size of about 600 m (part of this area may be caused by camera blooming). Unfortunately nebulous meteors were recorded with long exposition time. It is estimated by Taylor et al. (2000), that only about 8% of Leonid meteors (in their data sample of about 100 meteors) demonstrate unusual structure features.

Extremely interesting observations were done by Dr.Stenbaek-Nielsen during Leonid 2001 MAC campaign (Stenbaek-Nielsen et al. 2002). Meteor image (estimated brightness -3^{mag}) demonstrated a lot of different structures up to hundred meters scale (Fig.6a). Meteor was observed at the altitudes 116–105 km. Very crude estimate of meteor lateral size δX is given on Fig.6b. It corresponds to the boundary of constant intensity because the central part of the images is overexposed.

Let us to estimate possible heated area. We will consider more wide range of meteor brightness (-2^{mag} - -7^{mag} meteors) for comparison. The masses of similar meteoroids are about 0.44–44 g and radii are about 0.5 – 2.2 cm (Jenniskens et al. 1999). Initial energy of similar meteoroids is 10^{13} 10^{15} ergs.

According to spectral observation the 2/3 of radiation is caused by atmospheric emissions (O, N, N2) (Borovička et al. 1999). Temperature of main radiative volume was estimated as about 4,000-5,000K both by vapor lines (main spectral component, (Borovička et al. 1999)) and air band (Jenniskens et al. 2000). We will consider only air in our estimates. What air volume is possible to heat up to 4,300K? Average density of undisturbed air may be assumed as 10^{-10} g/cm^3. The internal energy of air (T$\sim$4,300K, $\rho\sim$ 10^{-10} g/cm^3) is about 20 kJ/g (Kuznetsov 1965).

High frequency imager covered only a part of meteor trajectory. Suppose a half of total meteoroid energy been released on this part of trajectory, we will obtain the heated volume about 2.5 $\cdot$ 10^{11}-10^{13} cm^3. Assuming cylindrical shape with length 10 km the radius will be equal 2.8–28 m. That gives us an crude estimate of the width of luminous area. The nonuniform energy release along trajectory may lead to increase of disturbed area size. The upper estimate may be found assuming all meteoroid energy been released in a point. Radius of heated spherical volume will be about 40–190 m at H=105 km. Corresponding curves are given on Fig.6b and marked R(-7) and R(-2). According to our estimates disturbed area width cannot be larger than 200 m. Meters - tens meters width (3–30 m) seems to be more probable. Meters-size width coincides with theoretical prediction. Excited area may reach tens meters, if to take into account cloud influence on surrounding air. Fast particles may escape from vapor cloud or be sputtered from it. Some air particles may be reflected from formed cloud. The beam of these fast particles may increase disturbed area. Disturbed area assuming energy transfer on about 10ℓ is marked at Fig.6b. All lateral size estimates are smaller than estimated

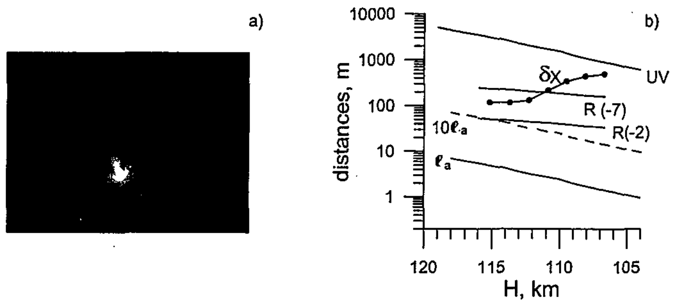

Fig. 6: a) High frequency image of meteor obtained by H.C.Stenbaek-Nielsen b) Estimates of possible disturbed area size. See discussion in text.

meteor size δX. All our estimates are done suggesting equilibrium conditions.

The large lateral size of luminous area is still an open question. The pre-dissociation and preionization by UV radiation from hot area nearby meteor head may be suggested (Stanbaek-Nilsen et al. 2002). Estimate of UV photons free length is marked on Fig.6b. Their penetration length is enough to excite large area, but the efficiency of such energy conversion is under question. Nonequilibrium effects (when the area is excited but not heated) may play role in that picture. Although it should be mentioned that high degree of nonequilibrium is in contradiction with near equilibrium condition of radiation found in meteor spectra. Some plasma effects also may contribute into this interesting phenomenon. But currently, there is no clear explanation what is the physical reason for observed features. We hope that further observations from planned 2002 Leonid MAC mission may help us to understand this and others unusual data.

4.1 Conclusions

For fast meteor bodies (0.01 – 10 cm sized) presence of evaporated material is essential. A particle beam model describes the air-meteoroid vapor interaction well. 1D approximation adjusted by 2D modeling and supplemented with a more complete physical model, may be used to study this problem. Precise vapor parameters values depend on assumed geometry (1D or 2D), on model of momentum transfer and mass stripping, on parameters of substance. And we have some uncertainties here. Nevertheless the main features are evident. Vapor cloud is formed around body. Given body size the momentum transfer and vapor radiation should be taken into account with altitude decrease.

The direct MC simulation estimates the fraction of energy transferred to the meteoroid and the conditions of meteoroid shielding. The deposition length equals approximately 10 mean free paths of the most penetrating primary particles and of vapor recoil fast particles. Consideration of particle dynamics in detail shows - the impinging air particles initiate the collisions - main air-cloud interaction is determined both by air-vapor and fast vapor-vapor particles collisions. The spatial distribution of absorbed energy is determined mainly by the energy transport of several generations($\sim$8) of vapor particles.

Interesting observations recently appeared need to be explained in future. Currently existing models do not provide this explanation, but are the basis to begin from.

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