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Fragmentation and densities of meteoroids

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Abstract. The phenomenon of meteoroid fragmentation in the Earth's atmosphere was recorded repeatedly by means of different methods and especially using the photographic technique of instantaneous exposure. Among the four principal forms of fragmentation, the quasi-continuous fragmentation, i.e. a gradual release of the smallest fragments from the surface of a parent meteoroid and their subsequent evaporation, is most common. The analysis of photographic observations shows that a substantial fraction of meteoroids is exposed to this type of fragmentation. According to the theory of quasi-continuous fragmentation and on the basis of light curves of meteors photographed in Dushanbe (Tajikistan), the mean bulk densities of meteoroids belonging to six meteoroid streams and the sporadic background have been determined, which vary in the range from 0.4 g cm^{-3} (Leonids) to 2.9 g cm^{-3} (Geminids).

Key words. meteors, meteoroids

1. Introduction

At present there is no doubt that the majority of meteoroids are the products of disintegration of cometary nuclei and asteroids. Thus the investigation of meteoroid orbits and physical characteristics is important not only for meteor astronomy but also for the understanding of physical features of the meteoroids' parent bodies.

According to the classical physical theory of meteors, meteoroids are considered to be solid stony or iron bodies with densities of 3.5 and 7.7 g cm^{-3}, respectively (Levin 1956). The results of photographic observation of meteors with Super-Schmidt cameras, namely, the discrepancy between the values of meteoroid masses determined from their light curves and from the drag equation, and short trails of Draconids, led to the concepts of fragmentation (Jacchia 1955) and "dust-ball meteoroids" (Opik 1958). Moreover, comparison of photometric and dynamical masses of meteoroids with an appreciable decelaration led to the conclusion of extraordinarily low densities of meteoroids (0.01–1 g cm^{-3}). Thus on the basis of the 413 precisely reduced trajectories of meteors, photographed by the Harvard Super-Schmidt cameras, Jacchia (1967) determined the average bulk densities of meteoroids to be 0.26 g cm^{-3}. Verniani (1967, 1969) analysed the results of determinations of meteoroids densities from Super-Schmidt meteors and came to the conclusion that the average meteoroid density of the majority of showers varies from 0.14 g cm^{-3} to 0.63 g cm^{-3}, and the average density of sporadic meteoroids is equal to 0.28 g cm^{-3}. Meteoroid densities also have been estimated by Verniani (1973) from radar observations of 5757 meteors from +6.5 to +10 mag to be 0.8 g cm^{-3}.

Starting from the observational data on the heights of meteors and fireballs produced by the meteoroids in a wide mass range from 10^{-4} g to 10^{8} g, Ceplecha (1977) concluded that according to their structure and composition the meteoroids form three main groups: 1) ordinary chondrites, with a mean density of 3.7 g cm^{-3}; 2) carbonaceous chondrites, with a mean density of 2.1 g cm^{-3}; 3) "cometary" material with a density from 0.2 to 1 g cm^{-3}.

The discrepancy between Verniani's and Ceplecha's evaluations of meteoroid densities might be explaned not only by the differences in the methods used, but also because of the fact that the method of determination of bulk densities from drag and luminosity equations is applicable only to single non-fragmenting meteoroids, that cannot be considered as satisfactory.

All in all, the discrepancy between the data from different methods of determination of meteoroid densities suggested the necessity to improve the physical theory of meteors taking into account meteoroid fragmentation in the Earth's atmosphere (see e.g. Lebedinets 1980; Novikov et al. 1984; Babadzhanov et al. 1988; Ceplecha & McCrosky 1992; Ceplecha et al. 1993; Ceplecha 1995).

2. Fragmentation of meteoroids

Fragmentation of meteoroids in the Earth's atmosphere has been recorded by both visual and photographic observations of meteors (Astapovich 1958). The results of photographic observations carried out using the

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method of instantaneous exposure (5.6×10^{-4} s each) showed this phenomenon the most strikingly and completely (Babadzhanov 1983; Babadzhanov & Kramer 1967). Atmospheric fragmentation of the unique fireball of −13 visual magnitude, that proceeded the fall of the Peekskill meteorite on October 9th, 1992, was videographed by at least 16 videographers (Beech et al. 1995). The videorecords also showed two time-resolved flares of this fireball. R. Hawkes (see Beech et al. 1995) found that the characteristics of the most pronounced flare are reasonably well explained by the simultaneous ejection of about 1000 grains, each of mass ∼1 g. The Peekskill meteorite is the fourth meteorite in history for which the orbital parameters have been determined. At present one can consider as established that fragmentation is a normal type of ablation for the majority of meteoroids producing meteors registered by photographic and radar methods. Levin (1962, 1963), Lebedinets (1980), Bronshten (1981), Ceplecha & McCrosky (1992), Ceplecha et al. (1993) showed that neglecting fragmentation in the interpretation of meteor observations may lead to erroneous results.

Analysing the data on photographic observations of meteors, Levin (1962) distinguished four main forms of meteoroid fragmentation: 1) the decay of a meteoroid into comparable large non-fragmenting debris; 2) the progressive disintegration of the original meteoroid into fragments, which continue to crumble into smaller debris; 3) the quasi-continuous fragmentation: a gradual release of the smallest fragments from the surface of a parent meteoroid and their subsequent evaporation; 4) the simultaneous ejection of a large number of small particles giving rise to meteor flares.

Photographic observations of meteors show that along the meteor trajectory the fragmentations of types 1) and 4) may occur more than once (Babadzhanov & Khaimov 1972; Ceplecha & McCrosky 1992; Ceplecha et al. 1993; Ceplecha 1995). It is quite probable that a meteoroid may undergo different combination of these fragmentation forms in the atmosphere (Babadzhanov et al. 1989).

Among the different forms of meteoroidal disintegration in the atmosphere described above, the quasi-continuous fragmentation is of greatest interest. Both meteor wakes and terminal blendings, as well as the results of laboratory experiments, provide evidence in favour of this mechanism of meteoroid disintegration. The most plausible mechanisms leading to this type of fragmentation may be (Lebedinets 1980; Bronshten 1981): 1) the blowing off of the melted meteoroid layer in the case of iron meteoroids; 2) the ejection of the heated surface owing to fast evaporation of more volatile admixtures; 3) the thermodestruction and blowing off of the surface layer; 4) the separation of solid grains, assuming a grainy structure of the body, due to the melting of the "glue" between grains (Hawkes & Jones 1975); 5) detachment of the fragments as a results of meteoroid "husking" (Bronshten 1981; Novikov et al. 1996).

Thus the mere fact of meteoroidal fragmentation in the Earth's atmosphere is not yet an indication of a crumbly structure of meteoroids. Comparatively large and dense stony meteoroids undergo fragmentation, too.

Estimations of meteoroid bulk densities taking into account quasi-continuous fragmentation were obtained by Novikov et al. (1984, 1996), but a shortcoming of their work is that the theoretical heights of fragmentation beginning and the termination of meteor phenomena were identified by means of the photographed heights of meteor appearance and disappearance, and this cannot be considered as satisfactory.

Basic equations of the theory of meteoroid quasi-continuous fragmentation were used by Lebedinets (1987a, 1987b) for the analysis of observed decelerations of faint photographic meteors and estimation of meteoroid densities. Using a mathematical simulation of the observed deceleration of Super-Schmidt meteors, Lebedinets (1987a, 1987b) estimated the bulk density of 190 meteoroids (92 sporadic and 98 shower) of mass from 0.1 to 1 g. It was found that out of 92 sporadic meteors 57 (or 62%) were produced by meteoroids similar to carbonaceous chondrites, 22 (or 24%) by meteoroids similar to ordinary chondrites, 8 (or 9%) by iron meteoroids, 4 by iron-stone meteoroids, and 3 by crumbling bodies of the "dust ball" type. In the case of shower meteors, the meteoroids of carbonaceous chondrite type and ordinary chondrite type were found more often, namely 48% and 29%, but the meteoroids of iron and of stone-iron types, and very crumbly bodies, interspersed with free ice, are found rarely, only 5%, 6% and 12%.

The main shortcoming of Lebedinets (1987a, 1987b) is that when determining meteoroid densities the meteor light curves are not taken into consideration. The value and reliability of obtained results would increase considerably if the same meteors were analyzed by different methods.

Two-station photographic observations of meteors allow one to study in detail the processes of disintegration of meteoroids in the Earth's atmosphere as well as the meteor phenomena. From photographic observations of meteors in Dushanbe, Tajikistan, on the basis of the light curves of meteors and taking into account the quasi-continuous fragmentation, we present below the results of determination of the bulk densities of meteoroids belonging to different streams. The results of the determination of atmospheric trajectories and orbital elements of meteors, whose light curves were used for the determination of the bulk densities of meteoroids, were published earlier by Babadzhanov (1963), Babadzhanov et al. (1966, 1969, 1982, 1998) and now are available at the IAU Meteor Data Center in Lund, Sweden (Lindblad 1994).

3. Determination of meteoroid densities taking into account quasi-continuous fragmentation

The light curves of meteors are indicative of meteoroid ablation processes during their flights in the atmosphere.

Photographic observations of meteors were carried out at Dushanbe using both the usual and the instantaneous methods. Some unique meteor photographs obtained in Dushanbe by the method of instantaneous exposure with exposure of 5.6×10^{-4} s show clearly the effects of different types of meteoroid fragmentation. The most common type is the quasi-continuous fragmentation forming the short-lived meteor wakes of up to several tens of metres in length. Instantaneous images of such meteors have a drop-like shape.

The theory of quasi-continuous fragmentation has been well developed by now. The formulas describing the variation of meteor luminosity along its visible trajectory depending on atmospheric density and parameters of quasi-continuous fragmentation have been obtained. According to this theory (Lebedinets 1980; Kalenichenko 1980; Novikov et al. 1984, 1998; Babadzhanov et al. 1988) the common expression describing the meteor luminosity along its trajectory is:

$$I(\rho) = \frac{9\tau_\nu M_0 V_0^3 \cos Z_\mathrm{R}}{2H(R_0 R_1)^3}\Big\{F_1(\rho)\Theta(a-\rho) + R_1^3 F_2(\rho)\Theta \times(\rho-a)\Theta(b-\rho) + \frac{1}{30}F_3(\rho)\Theta(\rho-b)\Theta(\rho_\mathrm{e}-\rho)\Big\}, \quad (1)$$

where

$$F_1(\rho) = \rho\Big\{\frac{1}{3}(\rho_\mathrm{e}-\rho)^2\left[R_1^3-(a-\rho)^3\right] - \frac{1}{2}(\rho_\mathrm{e}-\rho) \times\left[R_1^4-(a-\rho)^4\right] + \frac{1}{5}\left[R_1^5-(a-\rho)^5\right]\Big\} \quad (2)$$

$$F_2(\rho) = \rho\Big\{\frac{1}{3}(\rho_\mathrm{e}-\rho)^2 - \frac{1}{2}R_1(\rho_\mathrm{e}-\rho) + \frac{1}{5}R_1^2\Big\}, \quad (3)$$

$$F_3(\rho) = \rho(\rho_\mathrm{e}-\rho)^5, \quad (4)$$

$$a = \rho_\mathrm{e} - R_0, \quad b = \rho_\mathrm{e} - R_1, \quad (5)$$

$I(\rho)$ is the meteor luminosity at the height where the atmospheric density is equal to ρ; τ_ν, M_0, V_0 are the luminous efficiency, pre-atmospheric meteoroid mass and velocity, respectively; H is the scale height; Z_R is the zenith distance of the meteor radiant; ρ_e is the atmospheric density at the end height of the meteor phenomenon:

$$\rho_\mathrm{e} = 2\rho_\mathrm{m} + 0.75R_1 + \sqrt{\rho_\mathrm{m}^2 - 0.0375R_1^2} \quad (6)$$

deduced from a condition that the maximum of the light curve is in the range $a \le \rho_\mathrm{m} \le b$; ρ_m is the atmospheric density at the height of maximum luminosity, and ρ the atmospheric density at a arbitrary point in the meteor trajectory; a is the atmospheric density at the height of complete evaporation of fragments released at the moment of fragmentation beginning, while b is the atmospheric density at the height of the end of fragmentation; R_0 and R_1 are the parameters determining the quasi-continuous fragmentation:

$$R_0 = \frac{6Q_\mathrm{f} M_0^{1/3}\delta^{2/3}\cos Z_\mathrm{R}}{\Lambda A H V_0^2},$$

$$R_1 = \frac{2(Q-Q_\mathrm{f})m_0^{1/3}\delta_0^{2/3}\cos Z_\mathrm{R}}{\Lambda' A' H V_0^2}. \quad (7)$$

$Q_\mathrm{f} = 2\times10^{10}$ erg g^{-1} (Hawkes & Jones 1975; Kruchinenko 1982) being the specific energy of meteoroid fragmentation, while $Q = 8 \times 10^{10}$ erg g^{-1} is the specific energy of heating and evaporation of meteoric matter; Λ, A, δ are the heat transfer coefficient, the shape factor and the meteoroid density, respectively; Λ', A', δ_0 – the same values for the fragments; m_0 is the fragment mass; $\Theta(x)$ is Heavyside's unit step function: $\Theta(x) = 1$ at $x > 0$ and $\Theta(x) = 0$ at $x \le 0$.

In the case $R_1 \to 0$, that corresponds to very small fragments and to a condition $Q = Q_\mathrm{f}$, the Eq. (1) coincides with the conventional equation of meteor light curves:

$$I = \frac{9I_\mathrm{max}}{4}\frac{\rho}{\rho_\mathrm{m}}\left[1-\frac{\rho}{3\rho_\mathrm{m}}\right]^2, \quad (8)$$

where

$$I_\mathrm{max} = \frac{2\tau_\nu M_0 V_0^3 \cos Z_\mathrm{R}}{9H}, \quad \rho_\mathrm{m} = \frac{2QM_0^{1/3}\delta^{2/3}\cos Z_\mathrm{R}}{\Lambda A H V_0^2}. \quad (9)$$

The meteoroid bulk density and mass of fragments may be estimated if the values of Λ, Λ', A, A', and δ_0 are known a priori. Meteors detected in the Dushanbe photographs are bright and produced by meteoroids of mass greater than 0.01 g. According to Lebedinets (1991), for large meteoroids of mass between 0.01 g and 10 g the heat transfer coefficient depends on mass M_0 as

$$\Lambda = \Lambda_0 + (1-\Lambda_0)\exp(-kM_0), \quad (10)$$

where $\Lambda_0 = 0.03, k = 0.25\,\mathrm{g}^{-1}$. It is assumed that $A = 1.5, A' = 1.21, H = 6$ km, $\Lambda' = 1$ and $\delta_0 = 2.5$ g cm^{-3}.

Using the observed values of M_0, V_0, Z_R and the light curves of meteors, by the method of successive approximations we determined the values of meteoroid bulk densities and fragment masses (i.e. the parameters R_0 and R_1) for which the theoretical and observed meteor light curves are in the best agreement.

Simulations of the meteor light curves were carried out for meteoroid bulk densities between 10^{-2} and 10 g cm^{-3} and a mass of fragments between 10^{-10} and 10^{-2} g. We adopted as reliable the values of meteoroid bulk densities for which the mean deviation of the theoretical light curve from the observed one was minimum. As an example, Fig. 1 shows the results of simulations of three meteor light curves where the absolute meteor magnitude Mag is plotted against the altitude. As is seen, the observed light curves of the examined meteors (solid lines) correspond to theoretical ones calculated taking into account the quasi-continuous fragmentation.

An analysis of results shows that the observed parameters and light curves of 111 out of 197 bright meteors photographed in Dushanbe are described sufficiently well by the theory of quasi-continuous fragmentation. This is about 56% of the total number of investigated meteors. It was impossible to simulate the light curves of 86 meteors (44%) within the framework of the theory of quasi-continuous fragmentation. Apparently, these meteors were produced by meteoroids which undergo another form of

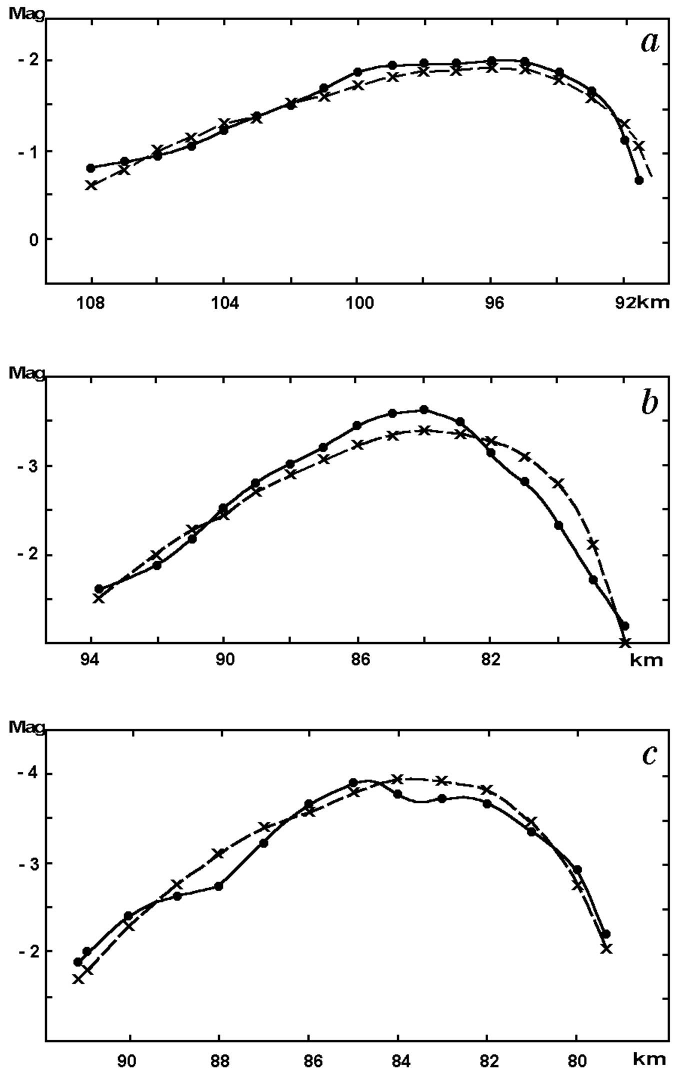

Fig. 1. Observed (dots) and theoretical (×) light curves of the meteors: **a)** N 641852, Perseid, $M_0 = .136$ g, $V_0 = 60.2$ km s^{-1}, $\cos Z_R = .868$; **b)** N 7908461, δ-Aquarid, $M_0 = 2.49$ g, $V_0 = 42.7$ km s^{-1}, $\cos Z_R = .573$; **c)** N 584865, Sporadic, $M_0 = 2.10$ g, $V_0 = 43.1$ km s^{-1}, $\cos Z_R = .794$.

fragmentation, and for which a more complicated simulation is necessary.

The results of determination of the mean bulk densities and their standard deviations for meteoroids belonging to different streams and sporadic background are given in the third column of Table 1, where N is the number of meteors used for determination of the mean values of bulk densities.

It turns out that the Geminid meteoroids have the largest bulk density average of 2.9 g cm^{-3}, which is in accordance with the results of Ceplecha & McCrosky (1992) obtained from photographic observations taking into account the "gross" fragmentation. The density of the Geminid meteoroids calculated without taking into account the fragmentation (Verniani 1969; Tokhtasyev 1978) is of 1 g cm^{-3}, i.e. three times less than when taking account of meteoroid fragmentation.

Table 1. Meteoroid densities.

Meteor shower	Parent body	δ g/cm^3	N
Perseids	109P/Swift − Tutlle	1.3 ± 0.2	44
Leonids	55P/Tempel − Tutlle	0.4 ± 0.1	6
Geminids	3200 Phaethon	2.9 ± 0.6	8
Quadrantids	96P/Machholz1	1.9 ± 0.2	3
δ-Aquarids	96P/Machholz1	2.4 ± 0.6	8
Taurids	2P/Encke	1.5 ± 0.2	3
Sporadic		2.2 ± 0.3	39

The Leonid meteoroids are possessed by the lowest average bulk densities of 0.4 g cm^{-3}. The mean bulk density of meteoroids of other streams are in the range from 1.3 to 2.4 g cm^{-3} and that of sporadic meteoroids is equal to 2.2 g cm^{-3}.

From Table 1 it follows that all the meteoroid densities are similar to the densities of carbonaceous chondrites and "cometary" material.

4. Conclusions

According to the theory of quasi-continuous fragmentation of meteoroids, on the basis of light curves of 111 bright meteors photographed in Dushanbe the mean bulk densities of meteoroids belonging to different streams have been estimated, which vary in the range from 0.4 g cm^{-3} (Leonids) to 2.9 g cm^{-3} (Geminids). The mean bulk density of sporadic meteoroids is equal to 2.2 g cm^{-3}. On average, the bulk densities of meteoroids are of one order larger than proposed before, without taking into account the fragmentation.

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