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Analytical modelling of the mass loss, light curve and energy deposition of the Chelyabinsk bolide using the developed fragmentation model

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Abstract

The model of atmospheric fragmentation of large meteoroids is developed. The analytical solution of equations for meteor physics is obtained for the mass loss, energy deposition, light curve and the altitude, where the maximum of this curve is reached. This solution together with proposed fragmentation model are applied to study the Chelyabinsk event. Comparison of analytical solution for light curve and energy deposition with observational data is made.

1. Introduction

Most of large meteoroids are disrupted during their entry into the atmosphere. There are different approaches to modelling of meteoroid fragmentation. In some models it is assumed that fragments move independently (few large fragments or progressive fragmentation). In this study the other approach is applied – the breakup of a meteoroid into a cloud of small pieces which move with the common shock wave as a single body. This liquid-like model was proposed in [7] for small melt meteoroids when sphere is continuously deformed to flattened spheroid by the aerodynamical loading. This model when a body is expanding in a lateral direction and reducing in thickness in a flight direction was developed in detail in [4]. Later similar models were used in other papers [5, 6] and were named [6] “pancake” models.

2. Fragmentation model

We suggest a spherical shape of the meteoroid before start of breakup, then the meteoroid continues its flight as a cloud of fragments and vapor which fill in holes between fragments. We assume two related processes: flattening – the sphere is deformed to the flattened spheroid with ratio of axes k ($k \geq 1$), and the decrease of density of the fragmented meteoroid due to the increase of spacing between fragments.

The velocity of lateral expanding of the fragmented meteoroid was obtained by Grigoryan [4] in the form

$$\frac{dR_S}{dt} = 2k_r V \left(\frac{\rho}{\delta}\right)^{1/2} \tag{1}$$

Here V is the meteoroid velocity, δ is its density, R_s is the lateral cross-section radius, ρ is the atmosphere density, k_r is some function from the surface pressure distribution. Grigoryan assumes $k_r = ½$, that is for sphere. Then

$$\frac{dR_S}{dt} = V \left(\frac{\rho}{\delta}\right)^{1/2} \tag{2}$$

This formula is used and cited in many papers. We found function k_r for spheroid and obtained from (1)

$$\frac{dR_S}{dt} = \frac{V}{k} \left(\frac{\rho}{\delta}\right)^{1/2} \tag{3}$$

Hence the velocity of lateral expanding (flattening) essentially depends on degree of the flattening.

3. Analytical solution

The equations for meteor physics – equations of motion and ablation (mass loss) [2, 7] include drag and heat transfer coefficients. The analytic solution for the drag coefficient of spheroid in dependence on parameter k is obtained. The expression for radiative heat transfer coefficient of a spheroid is obtained with using literature data. In the assumption that the meteoroid mass decreases more rapidly than its velocity, the analytical solution for a large meteoroid of a spheroidal shape (with change of its density and parameter k along flight trajectory) is obtained for the mass loss, energy deposition, light curve and the altitude where the maximum of this curve is reached, in dependence on entry parameters of the meteoroid.

4. Chelyabinsk meteoroid

Based on the analysis of various video records of the Chelyabinsk superbolide on 15 February 2013, the trajectory, velocity, light curves of the bolide and energy deposition per unit height were determined [1, 3, 8]. Using the fragmentation model presented in this study, we obtained the analytical solution for the mass loss, light curve and energy deposition for the Chelyabinsk meteoroid and compared this solution with results based on the video data [1, 3, 9].

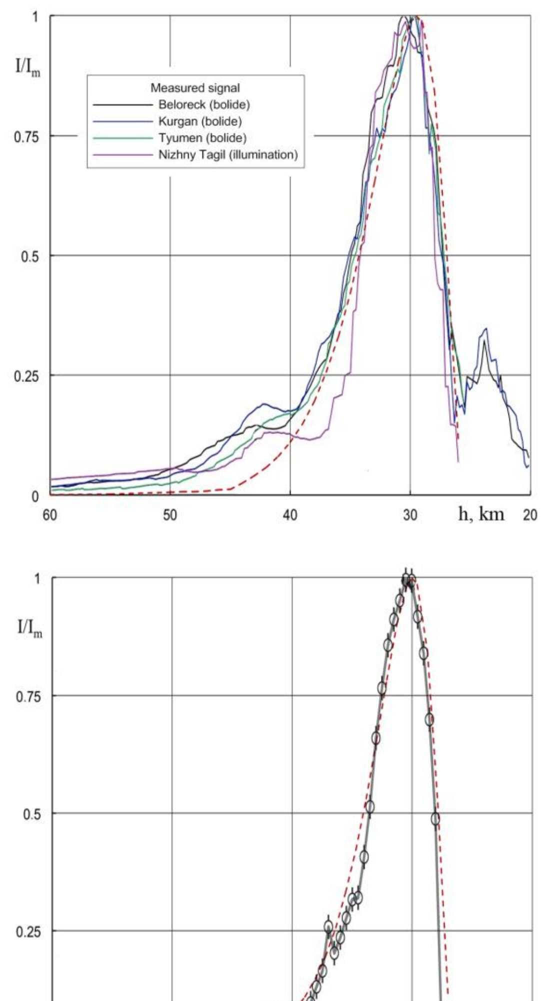

Figure 1: Light curves for the Chelyabinsk bolide. Comparison of the analytical solution (red dashed line) with the video data [1] (upper figure) and [9] (lower figure); *h* – the altitude, *t* – the time from the peak brightness.

Figure 1 shows comparison of the analytical light curve I/I_m normalized to maximum brightness (entry angle – 18°, velocity – 19 km/s, mass – $1.3{\cdot}10^7$ kg, bulk density – 3.3 kg/m^3, bulk strength – 0.7 MPa) with results of [1] and [9].

5. Summary and Conclusions

The proposed model of atmospheric fragmentation of large meteoroids differs from other pancake models in that it takes into account the decrease of density of the fragmented meteoroid and the dependence of the velocity of flattening on degree of this flattening. This model made it possible to obtain the simple analytical solution for the mass loss, energy deposition and light curve of the Chelyabinsk superbolide, which is in a satisfactory agreement with video observations down to altitude of 27 km.

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