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Two-stage destruction of meteoroids

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We consider the following scenario for the destruction of a rather large meteoroid body. During its movement through the atmosphere, the meteoroid suffers from aerodynamic forces, and gets repeatedly crushed. We assume that in this first stage of fragmentation, the meteoroid is divided into several rather big pieces. The resulting cloud of fragments of unknown shape, size, and quantity continues its path into the lower atmosphere. The second stage of fragmentation consists of the sudden destruction of a body into a cloud of small particles and dust. Due to extremely high temperatures at the surface of the fragments and in the gas around them, all of the meteoroids can melt in a short period of time. This phenomenon appears to the observer as a terminal flash.

1 Introduction

Observations of entries of bolides into the Earth's atmosphere prove their fragmentation and destruction in the atmosphere. Most meteoroids are destroyed by aerodynamic forces (Ceplecha et al., 1993; Ceplecha and ReVelle, 2005; Popova and Nemtchinov, 2008). The fragmentation could occur in two different ways. One way is progressive fragmentation, which means that the body breaks up into several particles. Alternatively, a meteoroid could be destroyed into a cloud of small dust particles. It is possible, however, that both fragmentation mechanisms are at work for the same meteoroid (Ceplecha et al., 1993). In this paper, we consider such a two-stage destruction.

2 Governing equations

As usual, we assume that the movement of the meteoroid is described by a standard set of equations including the equation for the movement of its center of mass and the equation of mass loss, which can be written as

$$\begin{cases} M\frac{\mathrm{d}V}{\mathrm{d}t} &= -\frac{1}{2}AC_{\mathrm{D}}\rho_{\mathrm{g}}V^2; \\ Q\frac{\mathrm{d}M}{\mathrm{d}t} &= -\frac{1}{2}AC_{\mathrm{H}}\rho_{\mathrm{g}}V^3, \end{cases} \tag{1}$$

with M the meteoroid's mass, V its velocity, A its cross-sectional area, ρ_{g} the density of the atmosphere around the meteoroid, C_{D} the drag coefficient, C_{H} the heat transfer coefficient, and Q the specific heat of ablation (effective enthalpy). The optical luminosity is proportional to the kinetic energy of the meteoroid mass and is due to the intensity of the ablation. The luminosity of the body (or particle) can be found as

$$I = -\tau\frac{V^2}{2}\frac{\mathrm{d}M}{\mathrm{d}t}, \tag{2}$$

with τ a dimensionless coefficient of luminosity (Ceplecha et al., 1993; Borovička et al., 1998).

3 Fragmentation and destruction of meteoroids in the atmosphere

We consider the motion of a rather big body, and assume that the body breaks up into several rather big pieces at the first stage of its fragmentation. Their shapes and sizes depend on the heterogeneity of the parent body. Further fragmentation of the cloud of particles occurs in a lower layer of atmosphere, where the aerodynamic forces increase. We assume that in the final stage the fragments break down into small pieces and produce a light flash known as a "thermal explosion" (Egorova and Lokhin, 2010; Egorova, 2012a; 2012b). This means that the fragments are in a hot cloud and may be subject to large thermal stresses, causing an additional fragmentation into smaller pieces that instantly evaporate, creating the explosion.

4 Duration and path length for each particle of the fragmented body

Without loss of generality, we assume a spherical shape for the fragments. Then, we can find the mass of the particle knowing its radius r and density ρ_{b}. Assuming the resistance and heat transfer coefficients to be constant, we may derive the following from the equations (1) of momentum and mass loss:

$$\begin{cases} V &= \frac{V_0}{1+\frac{3}{8}C_D\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{b}}}\frac{V_0}{r_0}t}; \\ r &= r_0 e^{-\frac{1}{6}\frac{C_D}{C_H Q}(V_0^2-V^2)}, \end{cases} \tag{3}$$

with V_0 and r_0 the velocity and radius of the meteoroid body upon entering the atmosphere.

We assume that the particles emit light until slowed down to a some critical velocity V_* which is no longer sufficient to maintain the heat at the surface of the body. Hence, we may derive the duration of the emission from (3):

$$t_* = \frac{8(V_0 - V_*)\rho_{\mathrm{b}}}{3V_0V_*\rho_{\mathrm{g}}C_D}r_0. \tag{4}$$

The path length of the meteor will then be

$$L = \int_0^{t_*} V \mathrm{d}t = \frac{8}{3}\frac{r_0 \rho_\mathrm{b}}{\rho_\mathrm{g} C_D} \ln\left(1 + \frac{V_0 - V_*}{V_*}\right). \quad (5)$$

5 The increase in light intensity at the first stage of fragmentation

In the first stage, the size of the particle depends on the parent body's heterogeneity, which is random, as was said before. We consider that the meteoroid fragments are all spherical and have all the same size. This assumption allows us to calculate the brightening as a result of the increase of the surface area:

$$\frac{I_\mathrm{fr}}{I_0} = \sqrt[3]{N}, \quad (6)$$

with N the number of fragments.

By the statistical theory of Weibull, the strength of the fragmented particles will increase (Popova and Nemtchinov, 2008). Knowing the strength of the fragmented particles, one may derive the altitude of the second fragmentation, and hence also the path length and duration before the next fragmentation.

We applied our theory for the SN94032 bolide (Popova and Nemtchinov, 2008) and the Košice meteorite fall (Borovička, 2012) and the results were in good agreement with the observational data.

6 Time and light intensity at the second (final) stage of fragmentation

Rapid destruction and evaporation of small fragments of the meteoroid causes the effect of a thermal explosion. We considered the thermal explosion caused by the rapid evaporation of the small fragments cloud with a typical fragment size range (Egorova, 2012a; 2012b). The luminosity of the final flare was calculated as an integral over the mass distribution:

$$I_\Sigma(t) = \int_{m_*}^{1} N_{m_0} \frac{\mathrm{d}}{\mathrm{d}m_0}\left(-\tau \frac{V^2}{2}\frac{\mathrm{d}m}{\mathrm{d}t}\right) \mathrm{d}m_0. \quad (7)$$

Here, we switched to dimensionless parameters by normalizing the largest mass to 1. Solving (7) allows us to find the intensity and the real duration of the final flare. We found that the calculated values of these parameters for the SN94032 bolide (Popova and Nemtchinov, 2008) and the Košice meteorite fall (Borovička, 2012) are close to the observed values, supporting our hypothesis of a two-stage fragmentation.

7 Conclusions

Using analytical solutions and simple estimates from the physical theory of meteors, we conclude that two-stage fragmentation can occur for rather bright fireballs.

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