Icarus 250 (2015) 544–552

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

New methodology to determine the terminal height of a fireball

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ARTICLE INFO

Article history:
Received 3 October 2014
Revised 9 December 2014
Accepted 21 December 2014
Available online 7 January 2015

Keywords:
Meteors
Meteorites
Near-Earth objects
Impact processes

ABSTRACT

Despite ablation and drag processes associated with atmospheric entry of meteoroids were a subject of intensive study over the last century, little attention was devoted to interpret the observed fireball terminal height. This is a key parameter because it not only depends on the initial mass, but also on the bulk physical properties of the meteoroids and hence on their ability to ablate in the atmosphere. In this work we have developed a new approach that is tested using the fireball terminal heights observed by the Meteorite Observation and Recovery Project operated in Canada between 1970 and 1985 (hereafter referred as MORP). We then compare them to the calculation made. Our results clearly show that the new methodology is able to forecast the degree of deepening of meteoroids in the Earth's atmosphere. Then, this approach has important applications in predicting the impact hazard from cm- to meter-sized bodies that are represented, in part, in the MORP bolide list.

1. Introduction

Deriving the meteoroid trajectories in the atmosphere is of particular interest to researchers. On the one hand, orbital parameters can be derived based on the time of appearance, meteor position and initial velocity, allowing us to estimate their parental relationship with parent bodies – asteroids and comets. On the other hand, a knowledge of physical parameters such as mass, velocity, deceleration, height, at different points of its trajectory turns out to be very useful so as to predict the energy of a possible surface impact, locate meteorite fall and/or understand the ablation and other mass loss mechanisms occurring along the flight.

Various photographic and video techniques have been developed to obtain the most accurate and systematic observations of meteors. Whipple and Jacchie (1957) (later modified by McCrosky and Posen (1968), Pecina and Ceplecha (1983) and Ceplecha et al. (1993)) derived a methodology by considering the separate meteor trails obtained when shuttering the video image. This technique allowed them to study the problem at shorter flight intervals. This analysis was dependent on the body properties' average values provided by the bibliography. However, a reliable theoretical flight model is still to be developed. The accuracy of theoretical results usually requires a very good precision in observation techniques. For example, Ceplecha et al. (1993) developed a theoretical model which included meteor fragmentation, but it needs very precise fireball records. Along the years different methods have been developed in order to increase the accuracy of the theoretical models.

One of the first theoretical models for meteors (known as Single Body Theory) was developed by Hoppe (1937). It was an extensive study of the flight mechanics and thermodynamics processes. Levin (1956, 1961) studied the meteoroids' atmospheric entry with account for fragmentation and deceleration. He concluded that the mass of the body is related to its middle section by means of a parameter that characterizes the rotation of the fireball.

Later on, Ceplecha and McCrosky (1976) explored which fireballs of the Prairie Network were ordinary chondrites. The authors considered the fireball terminal height as a main characteristic factor. It was concluded that carbonaceous material shall ablate more readily and, consequently, these bodies may have shorter trajectories. The authors derived an empirical criterion (Eq. (1)) that established a weighted relation between the fireball terminal height and other flight properties of the fireball (namely, air density at terminal height, ρ_E [g/cm^3], the preatmospheric mass, m_∞ [g], preatmospheric velocity, V_∞ [km/s], and the zenith distance of the meteor radiant, Z_R [degrees]).

$$PE = \log \rho_E + A \log m_\infty + B \log V_\infty + C \log(\cos Z_R) \quad (1)$$

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http://dx.doi.org/10.1016/j.icarus.2014.12.027
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This expression also has a theoretical meaning based on the single body theory, as explained in their work. Coefficients A, B and C are obtained by using a least squares fit to 156 fireballs of the Prairie Network (McCrosky and Boeschenstein, 1965). Owing to this criterion (Eq. (1)), Ceplecha and McCrosky (1976) classified the Prairie Network fireballs into four different groups. In their discussion they suggested that ordinary chondrites should all belong to the same range of PE values ($-4.60 < PE$).

Besides, Ceplecha and McCrosky (1976) took advantage of the fireballs' observed properties in order to shed more light in the validity of the previous criterion (Eq. (1)). Two parameters were used: K (the shape–density coefficient) [$cm^2\ g^{-2/3}$] and σ (ablation coefficient) [$s^2\ cm^{-2}$]. The average values (for all the observational measurements) are used to define a new parameter, SD:

$$SD = \langle log K\rangle + \langle log\,\sigma\rangle \tag{2}$$

The average numbers, $\langle log K\rangle$ and $\langle log\,\sigma\rangle$, are weighted by the ratio of the deceleration to its formal rms error. Then, SD is a parameter that has little influence from observational errors. As Ceplecha and McCrosky (1976) stated, SD depends on the second derivative of the observational measurements via these two refined numbers, whereas PE is chosen as the simplest possible empirical expression. Therefore, SD is a new criterion which can be compared against the PE criterion. These two parameters (1) and (2) turned out to be related when the meteor initial mass could be considered small or the ablation was large.

Slightly different methodology was suggested by Wetherill and Revelle (1981). They included four meteorite selection criteria to build up their classification. Wetherill and Revelle (1981), gave more importance to the dynamic mass than to the photometric mass; besides, they also took into account the deceleration of the body and the light curves to identify the survived meteorites among the fireballs registered by the Prairie Network. The authors highlighted the importance of the observed terminal height concluding that for meteorite-producing fireballs its value should agree with the theoretical value, calculated using dynamic mass, as well as with that of Lost City fireball to within 1.5 km, when scaled for mass, velocity, and entry angle in accordance with classical single body meteor theory.

In Revelle (1979), the study of the interaction between large meteoroids and the atmosphere is done via a quasi-simple ablation model. The results are compared to photographically recorded meteorite falls as well. Later publications have gathered and expanded the physical problem of the deceleration of meteoroids in the atmosphere (e.g. Bronshten, 1983).

Halliday et al. (1989a,b) studied observed fireball properties to derive the presence of correlations. They used 44 MORP recorded fireballs to classify as strong, moderate, weak or not having any correlation the observed data (i.e. initial velocity, total light emitted by the fireball, initial and end masses, initial and end heights, orbital elements, etc.). Despite of the observational errors (cameras not able to film all the trajectory, not clear sky, etc.), they found some strong correlations: mass lost by ablation versus the peak brightness, and duration of luminosity recorded by MORP versus zenith distance of the radiant.

Stulov et al. (1995), Stulov (1997) and Gritsevich (2007) proposed a new methodology. Instead of using the average values as input parameters, they gather all the unknown values into two new variables α (ballistic coefficient) and β (mass loss parameter), mathematically introducing similar idea with scaling of parameters as suggested by Wetherill and Revelle (1981). Adjusting the resulting equation to the trajectory observed, these new variables can be derived for each meteoroid. The resulting values allow to describe in details the meteoroid trajectory in the atmosphere and invent new classification scale for possible impacts (Gritsevich et al., 2011, 2012). This allows to determine other important parameters, such as preatmospheric and terminal mass values, ablation and shape change coefficients, as well as terminal height. The methodology to determine terminal height has been implemented for fully ablated fireballs by Gritsevich and Popelenskaya (2008). In the present study we significantly specify and expand the applicability range of this methodology by testing it on larger data set.

In the following sections we present the results of applying this last methodology to a large number of MORP fireballs, including suspected meteorite-producing events included in the table 6 by Halliday et al. (1996). Alternatively, we suggest a more accurate method of calculation. Section 2 takes a look on previous and present terminal height determinations. We then compare observed values to our derived values in Section 3. Section 4 contains our discussion. Finally the conclusions and suggestions for future research are presented in Section 5.

2. Theory

The equations of motion for a meteoroid entering the atmosphere projected onto the tangent and to the normal to the trajectory are well known. Once we consider some simplifications (see Gritsevich, 2010) we have:

$$M\frac{dV}{dt} = -\frac{1}{2}c_d\rho_a V^2 S \tag{3}$$

$$\frac{dh}{dt} = -V\sin\gamma \tag{4}$$

M is the body mass, V is its velocity, t is the time, h is the height above the planetary surface, γ is the local angle between the trajectory and the horizon, S is the area of the middle section of the body, ρ_a is the atmospheric density and c_d is the drag coefficient.

Eqs. (3), (4) are complemented by the equation for the variable mass of the body:

$$H^*\frac{dM}{dt} = -\frac{1}{2}c_h\rho_a V^3 S, \tag{5}$$

where H^* is the effective destruction enthalpy, and c_h is the heat exchange coefficient. Two other expressions are added to solve the problem. On the one hand, we suggest that the atmosphere is isothermal, and so $\rho = exp(-h/h_0)$, where h_0 is the scale height. On the other hand, from the research carried out by Levin (1956, 1961) we can assume that the middle section and the mass of the body are connected by the following relation $s = m^\mu$, where μ is a constant. The parameter μ characterizes the possible role of rotation during the flight and can be calculated based on the observed brightness of a fireball using the method proposed by Gritsevich and Koschny (2011). In Gritsevich (2008c) different values for μ are discussed. If $\mu = 0$ there is no body rotation, whereas if $\mu = 2/3$, the ablation of the body due to its rotation is uniform over the surface, and the shape factor does not change. Generally we have $0 < \mu < 2/3$. According to the recent results (Bouquet et al., 2014) the majority of the MORP fireballs were found to have μ values closer to 2/3.

We now introduce dimensionless variables, $M = M_e m$, $V = V_e v$, $h = h_0 y$, $\rho_a = \rho_0\rho$, $S = S_e s$. Here, the subscript e indicates the parameters at the entry to the atmosphere, h_0 is a planetary scale height (we use 7.16×10^3 m for the Earth) and ρ_0 is the atmospheric density near the planetary surface.

Taking into account all these previous considerations, we can turn the equation system (3)–(5) into the following equations (see Gritsevich, 2009):

$$m\frac{dv}{dy} = \alpha\rho v s \tag{6}$$

$$\frac{dm}{dy} = 2\alpha\beta\rho v^2 s \tag{7}$$