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Asteroid fragmentation approaches for modeling atmospheric energy deposition

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ABSTRACT

During asteroid entry, energy is deposited in the atmosphere through thermal ablation and momentum-loss due to aerodynamic drag. Analytic models of asteroid entry and breakup physics are used to compute the energy deposition, which can then be compared against measured light curves and used to estimate ground damage due to airburst events. This work assesses and compares energy deposition results from four existing approaches to asteroid breakup modeling, and presents a new model that combines key elements of those approaches. The existing approaches considered include a liquid drop or "pancake" model where the object is treated as a single deforming body, and a set of discrete fragment models where the object breaks progressively into individual fragments. The new model incorporates both independent fragments and aggregate debris clouds to represent a broader range of fragmentation behaviors and reproduce more detailed light curve features. All five models are used to estimate the energy deposition rate versus altitude for the Chelyabinsk meteor impact, and results are compared with an observationally derived energy deposition curve. Comparisons show that four of the five approaches are able to match the overall observed energy deposition profile, but the features of the combined model are needed to better replicate both the primary and secondary peaks of the Chelyabinsk curve.

1. Introduction

As an asteroid descends through Earth's atmosphere, drag forces convert portions of its kinetic energy into light, heat, and pressure. The rate of this energy conversion is referred to as energy deposition and is often used to estimate potential ground damage due to blast waves or thermal radiation in asteroid impact risk assessments (Motiwala et al., 2015; Stokes et al., 2003; Toon et al., 1997). A notable challenge in developing and validating energy deposition models for risk assessment is the lack of observational evidence, particularly on the scale of objects large enough to present a threat to the population. However, observed light curves from smaller objects can serve as a basis for comparing and guiding energy deposition models. To accomplish this, the models are used to match observed light curves and, once a desired match is obtained, inference about the object's breakup characteristics can be made based on the modeling approaches and parameters employed. Several existing studies (Popova et al., 2013; Revelle, 2007; Revelle, 2005) provide examples of such an approach.

In order to provide a foundation for such phenomenological inferences, it is instructive to first compare the underlying modeling assumptions to understand their capabilities and limitations in representing various aspects of breakup and energy deposition process. Because the specific fragmentations of a given object depend largely on unpredictable details of its internal structure, the goal of these comparisons is to establish and improve phenomenological representations of the overall breakup process, focusing more on average fragmentation rates and aerodynamic interactions rather than on individual fragment properties or resulting strewn fields.

Existing asteroid fragmentation models tend to follow either a liquid drop/pancake approach or a discrete fragment approach (Bland and Artemieva, 2006; Artemieva and Shuvalov, 2001). In the liquid drop models (Hills and Goda, 1993; Chyba et al., 1993), the bolide remains intact until it meets a specified flight condition, at which point it is permitted to deform and spread into a "pancake" shape. This broadening shape presents an increasing frontal area to the flow, which increases both the aerodynamic drag and mass

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ablation. Discrete fragment models (Revelle, 2007; Revelle, 2005; Mehta et al., 2015), on the other hand, treat the breakup as a successive series of fragmentation events that split the body into individual pieces. Hybrid models that combine discrete fragmentation and pancaking behaviors have been discussed to a limited extent in previous literature, but specific models have not been published. For example, Artemieva and Shuvalov (2001), Artemieva and Shuvalov (1996) discussed the notion of a "hybrid" model in the context of a computational simulation of discrete elements grouped to mimic a cloud, and Popova (2011) has shown results suggesting a hybrid energy deposition approach but does not present the details of a particular model.

This paper compares energy deposition curves from one liquid drop model and three discrete fragment models, and presents a new combination model developed to incorporate advantageous features of both approaches. The Chelyabinsk event provides a basis for comparing all five models. Specifically, the fragmentation parameters of each model are varied to reproduce the energy deposition profile derived from the light curve of Brown et al. (2013). The results are used to evaluate the advantages and limitations of the various approaches, and to suggest how energy deposition modeling can represent key entry events more generally. Due to the large uncertainties in the modeling parameters, the study concludes with a stochastic assessment using the newly developed combination model to examine sensitivity to the fragmentation assumptions and the range of energy deposition results they produce.

2. Model descriptions

The following sections give an overview of the five fragmentation models implemented to compute atmospheric energy deposition in this work. The models presented are: a continuous fragmentation pancake model; three discrete fragmentation models with collective wake, non-collective wake, and independent wake treatments; and a combination model incorporating both continuous and discrete fragmentation components.

The flight physics and breakup assumptions common to all the models are presented first, followed by specific descriptions of the fragmentation approaches for each model. The primary difference among the existing models is how they treat the fragment interaction and wake behavior in assuming collective or discrete bow shocks following breakup. From an energy deposition perspective, these differences manifest through differences in the projected frontal area, or drag area, compared to the system's mass. This ratio, described by the ballistic coefficient, measures how effectively the atmosphere slows the meteoroid. The drag area also impacts how much the air heats the meteoroid and ties directly to the mass ablation. For all of the current models, drag and ablation are the sources of energy deposited in the atmosphere. Finally, the atmospheric energy deposition computed from the flight and fragmentation is defined.

2.1. Flight physics

In all of the models considered, the standard equations for meteor physics (Opik, 1958) are integrated to determine the state of the bolide and its fragmentation components throughout their entry trajectory. Time derivatives of velocity v (Eq. (1)), flight path angle θ (Eq. (2)), and mass m (Eq. (3)) are computed every time step. Instead of specifying an explicit time step, however, a constant altitude increment, Δh, is specified and a corresponding time step is calculated based on the instantaneous velocity and flight path angle (Eq. (4)).

$$\frac{dv}{dt} = -\frac{\frac{1}{2}C_d A \rho_A v^2}{m} - g\sin\theta \tag{1}$$

$$\frac{d\theta}{dt} = \left(\frac{v}{R_E + h} - \frac{g}{v}\right)\cos\theta \tag{2}$$

$$\frac{dm}{dt} = -\frac{\frac{1}{2}\rho_A v^3 A C_H}{Q_{ab}} = -\frac{1}{2}\sigma_{ab} C_d \rho_A A v^3 \tag{3}$$

$$\Delta t = \frac{\Delta h}{v sin\theta} \tag{4}$$

$$g = g_0\left(\frac{R_E}{R_E + h}\right)^2;\ g_0 = -9.81\ m \cdot s^{-2} \tag{5}$$

In these equations, θ is the angle relative to horizontal, C_d is the drag coefficient,[1] A is the instantaneous cross-sectional area, ρ_A is the atmospheric density, g is the gravitational acceleration, R_E is the average radius of the Earth (6.371×10^6 m), h is the instantaneous altitude, and σ_{ab} is the ablation coefficient. In Eq. (3), the product of the ablation coefficient, σ_{ab}, and the drag coefficient, C_d, replaces the ratio of the heat transfer coefficient (C_H) to the effective heat of ablation (Q_{ab}). In the absence of shape-dependent ablation and drag physics, constant values of $\sigma_{ab} = 10^{-8}\ s^2 \cdot m^{-2}$ (Hills and Goda, 1993) and $C_d = 1.0$ are used.

Eqs. (1)–(3) are used to update the velocity, flight path angle, and mass at each altitude step, which is usually set to 10 m increments. The cross-sectional area, A, is also reduced based on the decreased mass, assuming constant, uniform density and spherical shape. For each iteration, the atmospheric density is interpolated from the 1976 standard atmosphere tables, and the gravitational acceleration is computed from Eq. (5). The derivatives are then recomputed and the process repeats until the bolide reaches the ground or the flow conditions reach the specified breakup criterion. Once fragmentation begins, flight integration is computed similarly for the resulting fragments and/or pancaking clouds, as described below for each model.

2.2. Breakup criteria

Following Stokes et al. (2003), Bland and Artemieva (2006), and Mehta et al. (2015), a breakup event is assumed to occur when the pressure, P, at the leading edge stagnation point of the bolide exceeds a specified breakup threshold, S, as defined by Eq. (6). Although this parameter is broadly referred to as "strength" for convenience, it does not represent a specific material property of the bolide, such as yield strength, compressive strength, or tensile strength. Rather, it acts as a generalized proxy for bulk/aggregate strength by representing the flight conditions under which the breakup behavior begins to manifest observably. While initial weakening, structural disruption, or debris shedding may begin earlier, the breakup criteria used here correlates the model's defined fragmentation behavior to the point at which the separation effects become physically significant to the flight dynamics and energy deposition.

$$\left(P = \rho_A v^2\right) \geq S \tag{6}$$

For models that allow multiple discrete fragmentations, the breakup strengths of the resulting fragments increase according to Eq. (7) (Artemieva and Shuvalov, 2001; Mehta et al., 2015; Weibull, 1951), where α is an exponential strength scaling parameter, and subscripts c and p refer to the child and parent fragment, respectively.

$$S_c = S_p\left(\frac{m_p}{m_c}\right)^{\alpha} \tag{7}$$

[1] The engineering convention is used for the drag coefficient in this paper, where drag is $\frac{1}{2}C_d A \rho_A v^2$. The factor of ½ is often omitted in the literature, so the C_d values may differ by a factor of two from the references.