ARTICLE IN PRESS
JID: YICAR [m5G;February 27, 2017;17:2]
Icarus 000 (2017) 1–21
Contents lists available at ScienceDirect
Icarus
journal homepage: www.elsevier.com/locate/icarus

A fragment-cloud model for asteroid breakup and atmospheric energy deposition

Lorien F. Wheeler[a,*], Paul J. Register[b], Donovan L. Mathias[c]

[a] CSRA, NASA Ames Research Center, MS 258-6, Moffett Field, CA 94035, United States
[b] Vanderbilt University, PMB 401807, 2301 Vanderbilt Place, Nashville, TN 37235, United States
[c] NASA Ames Research Center, MS 258-5, Moffett Field, CA 94035, United States

ARTICLE INFO

Article history:
Received 2 December 2016
Revised 13 February 2017
Accepted 17 February 2017
Available online xxx

ABSTRACT

As asteroids break up during atmospheric entry, they deposit energy that can be seen in flares of light and, if substantial enough, can produce damaging blast waves. Analytic models of asteroid breakup and energy deposition processes are needed in order to assess potential airburst hazards, and to enable inferences about asteroid properties or breakup physics to be made from comparisons with observed meteors. This paper presents a fragment-cloud model (FCM) that is able to represent a broad range of breakup behaviors and the resulting variations in energy deposition in ways that make it a useful tool for both applications. Sensitivity studies are performed to investigate how variations the model's fragmentation parameters affect the energy deposition results for asteroids 20–500 m in diameter. The model is also used to match observational data from the Chelyabinsk meteor and infer potential asteroid properties and representative modeling parameter ranges. Results illustrate how the model's fragmentation parameters can introduce different energy deposition features, and how much they affect the overall energy deposition rates, magnitudes, and altitudes that would drive ground damage for risk assessment applications.

1. Introduction

Throughout its history, Earth has been continually bombarded by asteroids. While the vast majority are small and burn up harmlessly in the atmosphere, rare impacts from larger objects have caused notable damage, ranging from the flattened forest in Tunguska (Vasilyev, 1998) to the K-T dinosaur extinction event (Alvarez et al., 1980). More recently, the 20-m asteroid that airburst over Chelyabinsk, Russia in 2013 injured 1500 people and caused $33 M in damage (Popova et al., 2013). This event motivated new assessments of the potential threat posed by midsized asteroids that may not be large enough to cause cratering or global-scale effects, but may still produce significant ground damage. To enable assessment of these risks, models of asteroid entry and breakup are needed.

As a bolide descends toward Earth and breaks up under aerodynamic forces, portions of its kinetic energy are transferred into the atmosphere through drag and thermal ablation. This energy produces observable light emissions and, if substantial enough, can generate blast overpressure waves or thermal radiation with the potential to cause significant ground damage. However, due to the rarity of sizeable asteroid bursts, limited data regarding pre-entry asteroid properties, and the complex multi-physics processes taking place during atmospheric entry, many key factors of the fragmentation and energy deposition process have remained uncertain.

The purpose of our work is to develop an analytic approach for modeling asteroid breakup, focused on capturing the atmospheric energy deposition that drives ground damage and observable light emission. These energy deposition results are used to evaluate airburst altitudes and severities for probabilistic asteroid impact risk assessments (Mathias et al., 2017), and can also be compared with energy deposition estimates from observed meteor light curves. A central challenge in developing such analytic models is including an effective balance of fidelity and efficiency. The model needs a sufficient, tractable set of modeling parameters that can reasonably represent key structural properties, combined with enough flexibility in the fragmentation modeling approach to produce a variety of breakup behaviors and energy deposition features. At the same time, the model must also remain simple enough to efficiently compute the millions of cases needed for probabilistic risk

* Corresponding author.
E-mail addresses: lorien.wheeler@nasa.gov (L.F. Wheeler), paul.j.register@vanderbilt.edu (P.J. Register), donovan.mathias@nasa.gov (D.L. Mathias).

http://dx.doi.org/10.1016/j.icarus.2017.02.011
0019-1035/

Please cite this article as: L.F. Wheeler et al., A fragment-cloud model for asteroid breakup and atmospheric energy deposition, Icarus (2017), http://dx.doi.org/10.1016/j.icarus.2017.02.011

assessment or explore the many parameter variations needed to match specific features of observed meteor entries.

We have developed a fragment-cloud model (FCM) that represents the breakup process using a combination of independent fragments and aggregate debris clouds. The model has the capability to vary key fragmentation parameters such as the number of fragments produced in each break, the relative mass distributions between fragments and debris clouds, and fragment strengths. Combining treatments of both discrete fragments and multiple debris clouds with these variable parameters enables the model to efficiently represent a wide variety of potential energy deposition features, from the broad, smooth flares associated with large bursts to multiple small flares from successive fragmentations. This capability provides a means to investigate how asteroids with different structures, material properties, and breakup mechanisms may deposit energy, and how those factors may affect potential ground damage.

Comparing different parameter variations can help to assess which factors most significantly affect energy deposition, which factors make little difference, and what aspects may warrant further study. In addition, adjusting the various modeling parameters to match observational data or high-fidelity simulation results can inform what parameter ranges or assumptions provide the best analytic proxies for the more complex underlying processes. Matching observed meteor entries can also potentially provide insight into the object's pre-entry characteristics, such as its structure, bulk density, porosity, or strength ranges (e.g., Brown et al., 2002; Ceplecha and ReVelle, 2005).

This paper gives an overview of the current fragment-cloud model and presents initial sensitivity studies investigating the effects of its various fragmentation parameters on energy deposition. The parameter variations assessed include the initial aerodynamic breakup strength, fragment strength scaling, the number of fragments per break, debris cloud mass per break, cloud dispersion rates, and ablation rates. We present the resulting effects on energy deposition features and discuss the implications for risk assessment applications and observational inferences. We then apply the model to reproduced observational data from the 2013 Chelyabinsk meteor. Results demonstrate the model's ability to estimate the energy deposited during realistic breakup processes, match specific energy deposition features, and provide insight into representative parameter ranges and asteroid properties.

1.1. Modeling background

A number of analytic asteroid entry models have been previously published, employing a range of simplified approaches for representing the breakup process. Many of these models tend to focus on describing specific aspects of the problem—such as strewn fields, crater formation, landed mass, or ablation—but are not applied to energy deposition or airburst assessment (e.g., Passey and Melosh, 1980; Melosh, 1981; Baldwin and Sheaffer, 1971; Borovička et al., 2007). The existing breakup models applicable to energy deposition and risk assessment tend to use either a "pancake" approach or a discrete fragmentation approach.

In the pancake type models, the fragmentation process is treated as a continuous deformation of an aggregate, single-body mass. The bolide remains intact until it meets a specified flight condition that triggers its disruption. It then begins to spread laterally into a pancake shape, decelerating and ablating as its frontal area grows. These models have typically been used to represent catastrophic fragmentation resulting in a single primary flare or burst, and are readily applicable to estimating burst altitudes for risk assessments and damage models. Hills and Goda (1993 , 1998) used a pancake approach to model energy deposition and airburst damage for various representative asteroid types. Chyba et al. (1993) applied a similar pancake approach to estimate energy deposition and burst altitudes for variations of the Tunguska event. These models have subsequently been adopted in several asteroid impact risk assessment studies (Stokes et al. 2003; Collins et al., 2005; Motiwala et al., 2015). However, the aggregate pancake treatment does not allow for variations that could result from non-uniform asteroid structures and the behavior of large, independent fragments.

Discrete or progressive fragment approaches, on the other hand, treat the breakup as a successive series of fragmentation events that split the body into individual pieces. The pieces increase in strength with each break, and then continue to undergo discrete fragmentations each time their flight conditions exceed their new strength. Baldwin and Sheaffer (1971) used this approach to represent swarms of an increasing number of fragmenting pieces in order to account for the effects of fragmentation on mass ablation and landed mass. ReVelle (2005, 2007) presents several discrete fragmentation treatments in which the fragments either fly side-by-side in formation (collective wake), or are shed into the wake (non-collective wake). Mehta et al. (2015) proposed an alternate treatment in which each fragment is assumed to separate enough to fly independently from the other fragments. These types of models often assume identical fragments in order to approximate general fragmentation trends and effects.

Purely pancake or discrete fragmentation models are useful for approximating simple, uniform flares or aggregate fragment effects, but individually are not able to capture the range of physical processes and energy deposition variations that occur in realistic breakup events (Register et al., 2017). An actual breakup process likely involves a combination of these behaviors, consisting of both larger, intact fragments that can reasonably be treated independently, and smaller debris or dust that is predominantly influenced by the common group aerodynamics. Hybrid model concepts like the FCM have been discussed in the literature to some extent (Popova, 2011; Artemieva and Shuvalov, 1996 , 2001), but specific analytic models involving both discrete and aggregate fragmentation components have not been presented. Popova et al. (2013) showed results of such a model applied to the Chelyabinsk meteor, but did not discuss its implementation or details. Broader studies investigating analytic hybrid model behavior, parameter sensitivities, or risk assessment applications are also lacking in the literature.

High-fidelity hydrocode simulations have also been used to study asteroid entry and breakup. These simulations generally consider specific impact events (e.g., Crawford et al., 1995; Boslough and Crawford, 2008; Zahnle and Mac Low, 1994) or investigate a specific aspect of the entry or breakup process (e.g., Robertson and Mathias, 2017; Korycansky et al., 2003; Shuvalov et al., 1999, 2002). However, hydrocodes are not currently used as part of impact risk models or to reproduce specific light curves. Even with recent gains in supercomputing power, these simulations remain too computationally expensive for the hundreds (Rumpf et al., 2016) to tens-of-millions (Mathias et al., 2017) of cases needed for statistical assessment of the impact threat. For example, the hydrocode simulations of Chelyabinsk-like meteor entries presented in Robertson and Mathias (2017) required around 48 h on 72 supercomputing cores (~3500 core-hours) for each single case. For observational comparisons, current hydrocode applications have not combined all of the relevant three-dimensional physics, object strength, mass ablation, thermal radiation, shock layer chemistry, etc. required to computationally create a synthetic light curve. Higher fidelity models also require specific definition of the pre-entry structure and material properties, which are not generally known. For these reasons, analytical approximations remain the most efficient modeling constructs for risk assessment and inferring pre-entry characteristics of observed meteors.