

Numerical and Probabilistic Analysis of Asteroid and Comet Impact Hazard Mitigation

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ABSTRACT

The possibility of asteroid and comet nucleus impacts on Earth has received significant recent media and scientific attention. Still, there are many outstanding questions about the correct response once a potentially hazardous object (PHO) is found. Nuclear explosives are often suggested as a deflection mechanism because they have a high internal energy per unit launch mass. However, major uncertainties remain about the use of nuclear explosives for hazard mitigation. There are large uncertainties in a PHO's physical response to a strong deflection or dispersion impulse like that delivered by nuclear munitions. Objects smaller than 100 m may be solid, and objects at all sizes may be "rubble piles" with large porosities and little strength [1]. Objects with these different properties would respond very differently, so the effects of object properties must be accounted for. Recent ground-based observations and missions to asteroids and comets have improved the planetary science community's understanding of these objects. Computational power and simulation capabilities have improved to such an extent that it is possible to numerically model the hazard mitigation problem from first principles. Before we know that explosive yield Y at height h or depth $-h$ from the target surface will produce a momentum change in or dispersion of a PHO, we must quantify the energy deposition into the system of particles that make up the PHO. Here we present the initial results of a parameter study in which we model the efficiency of energy deposition from a stand-off nuclear burst onto targets made of PHO constituent materials.

1. AN INTRODUCTION TO THE ASTEROID AND COMET NUCLEUS IMPACT HAZARD

Impacts have occurred throughout the history of our planetary system and indeed still occur now. The Tunguska event, the near miss of a similarly sized object in March 2009, the collision of Comet Shoemaker-Levy 9 with Jupiter in 1994, and the August 2009 impact of a 500-m-diameter object on Jupiter are reminders and warning signals that we should take seriously. The extinction of the dinosaurs has been attributed to the impact of a large asteroid or comet nucleus on Earth. Two large asteroids, which are each several hundred meters in diameter (99942 Apophis and 2004 VD17), will approach the Earth on 19 March 2029 and 4 May 2102, respectively. Besides the Tunguska air burst, there were several other notable events in the last hundred years: on 13 August 1930 in Curuçá, Amazonas, Brazil; on 12 February 1947 in Sikhote-Aligne, Russia; on 24 September 2002 in Vitim, Bodaybo, Russia; and the Carancas event on 15 September 2007 in Alta Plana, Peru [2]. PHOs strike the Earth with a frequency (commonly quoted as a function of object diameter) that is inversely correlated to their mass [3]. There are more small objects so these objects strike more often according to a predictable size-frequency distribution. Objects below a threshold diameter of 10 m have minimal consequences on the ground (similar to the Carancas impact of 2007), and an impact frequency of 1:10 years globally or 1:500 years in an urban area. There are a variety of ongoing surveys searching for small solar system objects and PHOs in particular. For example, the wide-field infrared survey explorer (WISE) infrared space telescope mission is just over halfway through its planned mission. During this mission it is expected to discover 100,000 previously unseen main-belt asteroids and 300 previously undiscovered near-Earth objects [4]. Earth-based surveys for PHOs continue as well. The PanSTARRS PS1 telescope has recently started its science mission, which will map the sky down to 24th magnitude, four magnitudes fainter than the current best data from the Catalina Sky Survey, and over a wider area of the sky. It is expected to significantly improve our catalog of small solar system objects, including increasing the number of known Kuiper belt objects by two orders of magnitude [5].

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The smallest impact events are seen as shooting stars. Several hundred metric tons of these small particles burn up in Earth's atmosphere every day. Larger objects, up to perhaps 50 m in diameter, depending on composition, may burn up as they transit Earth's atmosphere. Some objects in this size range may strike the ground as fragmented debris, as happened in the Carancas event in 2007, and some air bursts may have severe consequences on the surface, as was the case for the Tunguska event. Consequences of larger impacts are described in Collins et al. (2005) [6] and are analogous to the damage caused by the fireball from a nuclear detonation with much less ionizing radiation, and with the potential to be of much higher explosive yields. PHOs are defined as small solar system objects that meet two criteria: (1) they are asteroids or cometary nuclei with diameters larger than 150 m, and (2) approach within 0.05 astronomical units (5% of the Earth-Sun distance, or 7.5 million km) of Earth's orbit. The minimum diameter is under debate. It was originally set to be comparable with the object that caused the Tunguska airburst, but recent calculations by Boslough and Crawford indicate that the Tunguska impactor may have been as small as 30 m in diameter [7].

Asteroids are a diverse group of objects whose chemical compositions vary between carbonaceous objects (approximately 75% of the population of small inner solar system objects), stony basaltic objects (approximately 17%), and the remainder made up of nickel-iron objects [8]. Small asteroids may be solid objects, indicated by a rotation rate that generate centripetal forces larger than the gravitational forces generated by a mass that size, although this is under debate. Larger asteroids have been shattered repeatedly by collisions with other objects, and so tend to be unconsolidated piles of gravitationally bound rubble. This rubble pile composition makes them difficult to deflect, because they are very weak objects and cannot hold together when subjected to a large impulse. Research on the gravitational reassembly of disrupted objects [9, 10, 11] will have bearing on the question of hazard mitigation, because it will provide insight into the upper limit of the deflection forces that could be applied to a rubble pile as a function of time to Earth-intercept.

Less is known about comet nuclei. They are available for observation only infrequently when one enters the inner solar system, or a de-volatilized "stealth" comet is discovered among the asteroids [12]. Short period and "stealth" comets have a higher percentage of volatiles (water, hydrocarbon, carbon monoxide, and carbon dioxide ices), usually more than 50%, as opposed to less than 30% in asteroids. Long-period comets tend to contain higher percentages of volatiles because they have spent less time close to the sun. The structure of comet nuclei is a topic of current research. The NASA Stardust [13] and Deep Impact [14] missions have provided close observation of two comets and their nuclei. They found them to be very porous, delicate conglomerations of carbonaceous and silicate dust bound in an ice matrix.

2. HAZARD MITIGATION USING NUCLEAR DEVICES

Nuclear devices may be used to disrupt a PHO or modify its trajectory by vaporizing part of the object. The vapor expands, both removing mass from the object and pushing on the remaining solid portion. This energy deposition may either be done by burying the nuclear explosive within the target object, which significantly enhances the amount of energy absorbed by the PHO (see Weaver et al., this conference), or by detonating it at a given distance h from the surface of the object, and ablating surface material, which would be simpler to deploy, for example during a flyby.

Modern launch capabilities are limited to at most a 10,000 kg payload for an escape trajectory and only an additional 5,000 kg to low earth orbit. This limitation places severe restrictions on the explosive yield available for hazard mitigation in the near-term, and means that nuclear explosives would be required to provide the yield necessary to deflect very massive PHOs or those requiring a larger change in velocity because of a short lead time [15].

3. NUMERICAL MODELING OF THE INTERACTION OF A NUCLEAR DEVICE WITH A PHO

We use several different numerical methods to separately model energy deposition from x-rays, gamma rays, or

neutrons into different materials based on experimentally determined absorption patterns. These energy deposition processes are independent, so a piecemeal approach is physically reasonable. We use a Los Alamos National Laboratory (LANL) Monte Carlo particle transport simulation package similar to GEANT4 [16] and MCNP [17] to make probabilistic estimates of neutron or gamma-ray deposition. Once the location and amount of deposited energy is calculated, it can be sourced into the initial conditions of a radiation hydrocode model as internal energy.

A hydrocode is a computer modeling framework that uses the equations of fluid motion to study the response of different materials and objects to rates of strain and pressure wave propagation that are high relative to the object's properties (e.g., viscosity, strength, sound speed). Hydrocodes are widely used in planetary science to explore impact [18] and volcanic processes [19]. A radiation hydrocode further couples a model of radiation transport to the equations of fluid motion in order to more accurately model problems where a large amount of the energy in the system is carried by photons.

Fast push deflection of a PHO by a nuclear burst is just such a problem. According to Glasstone and Dolan (1977) [20], about half of the energy released from a nuclear explosion is in the form of thermal radiation. The actual percentage is a complicated function of yield, design, and environment. This partitioning makes thermal radiation a very important part of the problem, and means that hydrocodes without radiation transport are insufficient to the task of modeling this method of deflection.

Here we use the Radiation Grid Eulerian (RAGE) hydrocode developed by LANL in collaboration with Science Applications International Corporation (SAIC). RAGE is an Eulerian hydrocode with continuous adaptive mesh refinement (CAMR), a 'gray' diffusion model for radiative transfer using flux-limited nonequilibrium (two-temperature) diffusion, and tabular opacities. A variety of equations of state (EOS) are available to RAGE. Of these EOSs, the most accurate is SESAME. SESAME is a temperature-based, tabular EOS library maintained by the Mechanics of Materials and Equations of State group at LANL. RAGE has been through extensive verification and validation tests at every stage of its development. Validation for work on planetary impacts and hazard mitigation has been conducted by Pierazzo et al. (2008) [21], and Plesko et al. (2009), chapters 4-6 [22]. For descriptions of the code and verification and validation tests it has undergone, see Gittings et al. (2008) [23].

4. RESULTS: ENERGY DEPOSITION AND THE EFFECTS OF PHO COMPOSITION

We begin with a careful look at the coupling of energy from the burst to the PHO. Both explosive mitigation techniques and impacts can be thought of as inelastic collisions. The energy imparted to the PHO by the burst or impact is known. For an impactor, this variable is the kinetic energy; for a buried explosion, it is the yield of the burst; and for a stand-off burst, it is the fraction of the burst yield that intersects the surface of the PHO, which is simply the fraction of the yield that passes through the solid angle subtended by the PHO,

$$E_{in} = \frac{Y}{4\pi} \iint_S \frac{\hat{\mathbf{n}} \cdot d\mathbf{a}}{r^2},$$

where $\hat{\mathbf{n}}$ is a unit vector from the origin (usually the center of the burst), $d\mathbf{a}$ is the differential area of the patch of surface area subtended by the PHO, and r is the distance from the origin to the patch. We begin with a simple model of a burst at a height $h = 100$ m above a 1-km-radius target slab with a minimum cell resolution of $\Delta x = 10$ cm. In this geometry $E_{in} \approx 45\% Y$. For a hypothetical burst yield $Y = 16$ kt, the total energy incident on the target surface is $E_{in} \approx 7$ kt.

We vary the target material between a set of materials similar to those commonly found in potentially hazardous objects: basalt, granitic alluvium, iron, carbon, and water ice. We chose these materials because they are similar to the constituent materials of PHOs, and because their SESAME equations of state and opacities are well validated. Further experimental work is needed to develop equations of state and opacities that better represent observed meteoritic and cometary compositions.

It is possible to derive an upper bound on the amount of mass that could possibly be vaporized by E_{in} , given the thermodynamic properties of the target materials, and assuming the material is a pure substance. If a given material

were heated just to the point of vaporization, the energy it would take to vaporize one gram of the material is

$$Q_{\text{vap}} = \int_{T_i}^{T_f} mc_p dT + m \left(\frac{\Delta H_{\text{fus}}}{M} \right) + \int_{T_f}^{T_v} mc_p dT + m \left(\frac{\Delta H_{\text{vap}}}{M} \right),$$

where the material is heated from an initial temperature, (T_i), through the melting temperature (T_f), to the vaporization temperature, (T_v), assuming a material-specific heat capacity (c_p), heats of fusion (ΔH_{fus}) and vaporization (ΔH_{vap}), sample mass m , and molar mass M . From there, the upper limit on the amount of mass that could possibly be vaporized by the burst energy incident on the target is simply

$$m_{\text{v max}} = \frac{E_{\text{in}}}{Q_{\text{vap}}}.$$

These numbers are shown in red on Fig. 1 for several relevant materials. The actual vapor production will be substantially less. Energy will not be distributed uniformly, and a nonzero opacity of the vapor at the burst-facing surface means that some energy will be lost to heating mass that has already been ablated.

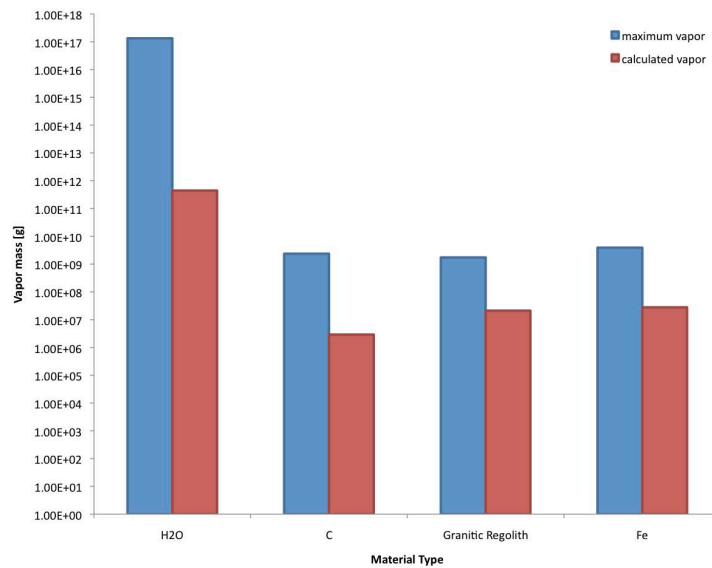


Fig. 1. The maximum possible vapor production from the amount of burst energy incident on the model target, compared with the amount of vapor predicted by the radiation hydrocode RAGE using the SESAME equation of state and opacity libraries for the listed materials. Calculated results are expected to also be somewhat optimistic. Calculated vapor masses range from about 0.0001% to 1% vaporization efficiency compared to the theoretical maximum.

Vapor mass estimates from radiation hydrocode calculations conducted according to the methods provided above yield a more cautious estimate, shown on Fig. 1 in blue. The calculated vapor masses range from about 0.0001% to 1% vaporization efficiency compared with the theoretical maximum. However, it is likely that these estimates are also larger than experimental results would provide, because the spatial resolution of the numerical models is necessarily larger than the relevant physical length scales in nature, so the energy deposition is averaged over a larger mass in the models than it would be *in situ*, likely leading to a larger mass at a lower temperature, but still above the vaporization threshold for the material type in question. Further validation work may be required to constrain this source of uncertainty.

5. RESULTS: SCENARIO-SPECIFIC DEFLECTION CASE STUDY

We are also exploring scenario-specific stand-off burst models. We use the same methods described above, but for a model target, we use a RADAR-generated shape model of asteroid 25143 Itokawa [24], which is not hazardous but has a composition similar to the majority of near Earth asteroids (NEO), and has been extensively studied by RADAR, and the Hayabusa mission and recent sample return. Asteroid Itokawa is better understood at this time than any other NEO [25].

In our initial models, we begin with a stand-off burst configuration recommended by Ahrens and Harris [26]. We use a stand-off distance of $h = 52$ m, or 40% of the shorter radius, a geometric optimum distance intended to irradiate the maximum surface area, and a burst yield of $Y = 10$ kt, as shown in Fig. 2.

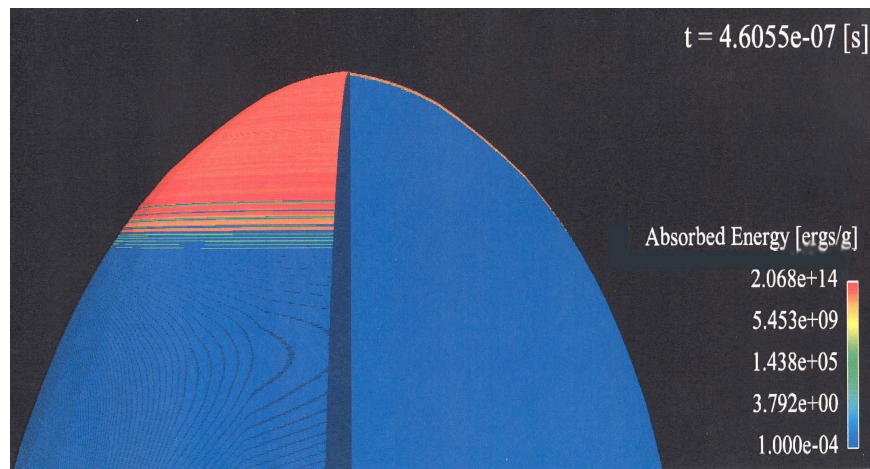


Fig. 2. Energy absorption model for a granitic alluvium target shaped like asteroid 25143 Itokawa, from a 10 kt stand-off burst at a height of 52 m.

In this model, we find that approximately 2 kt of energy are absorbed by the target, shown in Fig. 3a. This energy vaporizes approximately 3×10^8 g of target material, shown in Fig. 3b, or about 0.001% of the total target mass of 3.5×10^{13} g.

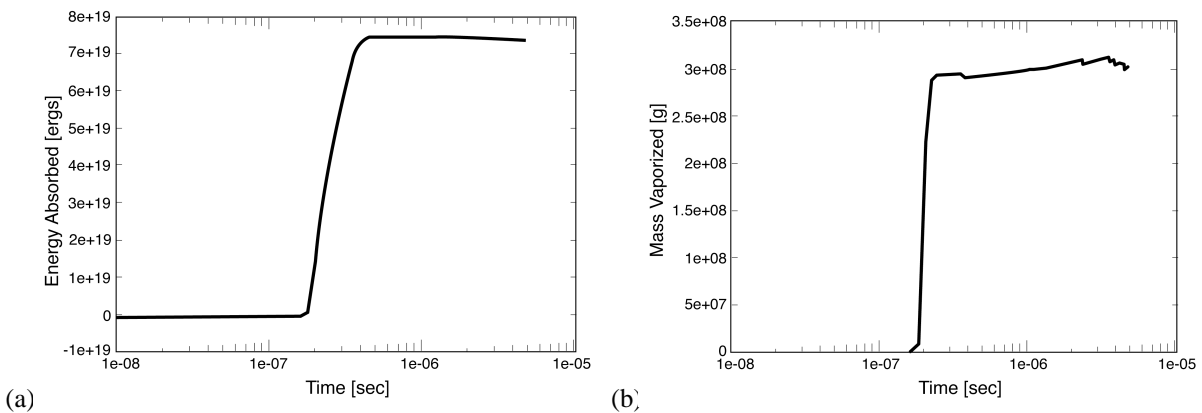


Fig. 3. (a) Energy absorbed by, and (b) mass vaporized from an asteroid Itokawa-like target from a 10 kt stand-off burst 52 meters above the target surface, as a function of time.

6. CONCLUSIONS AND FUTURE WORK

We have presented the results of numerical models of energy absorption from a hypothetical nuclear stand-off burst onto materials that are known constituents of PHOs, and preliminary results of an energy absorption study using a shape model from a real NEO. We used equations of state and opacities consistent with the composition of such an object. We find that the amount of vapor predicted by the numerical methods we used is within that allowed by upper-bound thermodynamic models.

The end goal of this work is to produce a “PHO Playbook,” a compilation of parameter studies, specific models of probable and technically challenging scenarios, and guidance on optimal stand-off distances, yields, and mitigation procedures, given knowledge of a hazardous object’s size, composition, spin, orbit, and time to intercept, in order to have that information available to decision makers well before the impact of an asteroid or comet nucleus threatens civilization again.

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