Planning Ahead for Asteroid and Comet Hazard Mitigation, Phase 1: Parameter Space Exploration and Scenario Modeling

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ABSTRACT

The mitigation of impact hazards resulting from Earth-approaching asteroids and comets has received much attention in the popular press. However, many questions remain about the near-term and long-term feasibility and appropriate application of all proposed methods. Recent and ongoing ground- and space-based observations of small solar-system body composition and dynamics have revolutionized our understanding of these bodies (e.g., Ryan (2000), Fujiwara et al. (2006), and Jedicke et al. (2006)). Ongoing increases in computing power and algorithm sophistication make it possible to calculate the response of these inhomogeneous objects to proposed mitigation techniques. Here we present the first phase of a comprehensive hazard mitigation planning effort undertaken by Southwest Research Institute and Los Alamos National Laboratory. We begin by reviewing the parameter space of the object's physical and chemical composition and trajectory. We then use the radiation hydrocode RAGE (Gittings et al. 2008), Monte Carlo N-Particle (MCNP) radiation transport (see Clement et al., this conference), and N-body dynamics codes to explore the effects these variations in object properties have on the coupling of energy into the object from a variety of mitigation techniques, including deflection and disruption by nuclear and conventional munitions, and a kinetic impactor.

1. AN INTRODUCTION TO POTENTIALLY HAZARDOUS OBJECTS

Asteroids and comet nuclei have collided with planets throughout the history of our planetary system. The evidence is clear from the impact craters on the Moon, Mars, Mercury, other planets and moons in our solar system, as well as from over 160 identified impact craters on Earth. These impacts have occurred throughout history of our planetary system and indeed still occur now. The Tunguska event (Boslough 2008), the near miss of a similarly sized object in March 2009 (Herald 2009), collision of Comet Shoemaker-Levy 9 with Jupiter in 1994, and the August 2009 impact of a 500-m-diameter object on Jupiter (Martinez 2009) 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. Zaitsev (2006) has listed six objects hurtling between Earth and the Moon since 1991. Two large asteroids, several hundred meters in size, 2004 MN4 = 99942 Apophis and 2004 VD17, will approach the Earth on 19 March 2029 and 4 May 2102, respectively. Besides the Tunguska event, 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 on 15 September 2007 in Alta Plana, near Lake Titicaca in Peru.

Asteroids are a diverse group of objects whose chemical composition vary between carbonaceous objects that make up about 75% of the population of small inner solar system objects, stony basaltic objects that make up another 17% , with the remainder made up of nickel-iron objects (Norton, 2002). 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 (see Holsapple, 2007). Larger asteroids have been shattered repeatedly by collisions with other objects, and so tend to be unconsolidated piles of gravitationally bound rubble. This 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 (e. g., Leinhardt 2000) will have bearing on the question of hazard mitigation, because it will provide insight into the upper limit of a the deflection forces that could be applied to a rubble pile as a function of time to Earth-intercept.

Much 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 (Huebner 2008). Short period and "stealth" comets have a higher percentage of volatiles (water, ammonia, and carbon dioxide ices), usually around 50%, as opposed to less than 30% in asteroids. Longer 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 (Brownlee 2003) and Deep Impact (REF) missions have provided close observation of two comets and their nuclei. They found them to be very porous, delicate conglomerations of carbonaceous and silicate material bound in an ice matrix.

Hazard mitigation is a complicated and multivariate problem. The PHO's chemical and physical composition, and time from discovery to Earth-intercept all have strong bearing on the efficacy of any proposed mitigation method. Given the observed physical weakness of most asteroids and cometary nuclei, the March 2007 NASA White Paper "Near-Earth Object Survey and Deflection Analysis of Alternatives" affirmed deflection as the most practical means of impact prevention, and identified nuclear bursts as the most effective and practical way to deflect objects in some cases.

2. PRAGMATIC HAZARD MITIGATION: "FAST PUSH" DEFLECTION

There are many proposed methods for deflecting a PHO. They fall roughly into two categories; "slow push" methods like solar sails, albedo modification, mechanical mass ejection, and gravity tractors, which are intended to impart the required change in velocity over years to decades, and "fast push" methods, which are intended to impart the required change in velocity effectively instantaneously through an explosion. The slow push methods that have been proposed would obviate concerns over object disruption, but are intended to work over time scales of years to decades, and so would require a substantial amount of time from the time of deployment to the time of potential impact in order for the process to work. On top of this, all of these proposed methods are untested and well beyond modern technical readiness levels for deployment in the case that a hazard is discovered with a time to Earth impact of less than a century. Fast push methods rely on well-tested technologies to launch, deploy, and provide the impulse, but are limited by modern launch mass limitations and uncertainties in the coupling of momentum from the explosion to the object. Modern launch capabilities are limited to at most a 10 ton payload for an escape trajectory , and only an additional 5 tons to low earth orbit. This places severe restrictions on the explosive yield available for a fast push deflection, and means that nuclear explosives would be required to provide the yield required to deflect massive PHOs, or those requiring a larger change in velocity because of a short lead time. Exploration of momentum coupling from the explosion to the PHO is part of this work.

3. RADIATION HYDROCODE MODELS OF DEFLECTION

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 and volcanic processes. (See, e.g., Benz and Asphaug (1999), Ogden et al. (2008)). 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 nuclear burst is just such a problem. According to Glasstone and Dolan (1977), 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 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 Los Alamos National Laboratory (LANL) in collaboration with SAIC. RAGE is an Eulerian hydrocode with continuous adaptive mesh refinement (CAMR), a gray diffusion radiation RAGE uses 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), and Plesko et al. (2009). For comprehensive descriptions of the code and verification and validation tests it has undergone, see Gittings et al. (2008) and Plesko (2009), chapters 4-6.

4. THE SIMPLEST CASE

For our initial studies, we use a fiducial 100 meter spherical basalt target. We do not model the nuclear munition in detail. The variable energy yield (y) is sourced instantaneously into a small aluminum sphere. This source is set a variable height (h) away from the near surface of the target. RAGE cannot allow a true vacuum, so we use a low density (~3×10^{-8} g/cm^3) solar wind composition gas for the background.

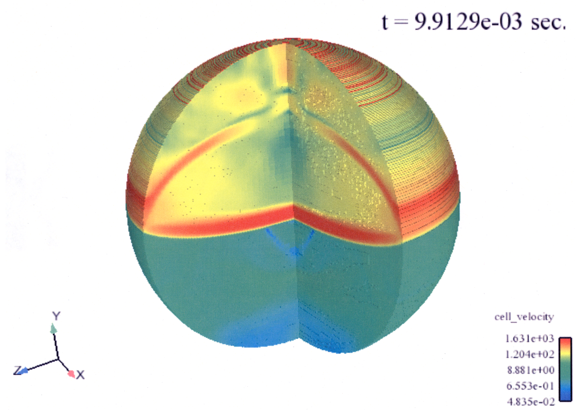

Fig. 1. Shock propagating through the simplest case model, with ablating material at the top surface moving at speeds of order 1 m/s.

A RAGE model of a Y = 100 kt burst at h = 70 m from a d = 100 m basalt sphere deforms the target and, by dt = 0.10 seconds, shows a center of mass velocity of v ~ 35 cm/s away from the burst location. The target surface temperature peaks at 3000-5000 K, within a solid angle of 10° from vertically below the burst.

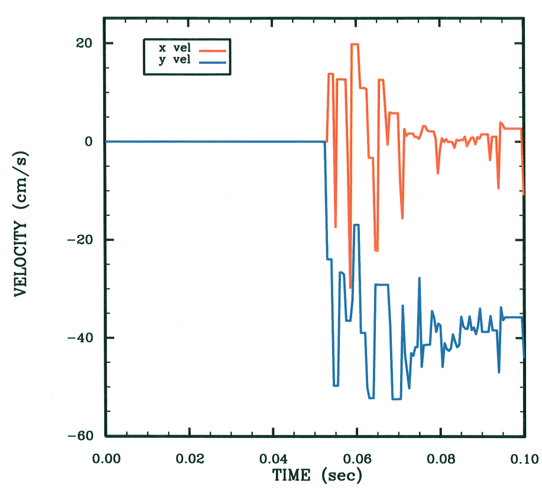

Fig. 2. Motion of Lagrangian tracer particles placed at the target sphere's center. There is a net velocity of 35 m/s away from the location of the stand off burst.

This simplest case model is the basis of ongoing parameter studies that we are using to explore the effects of target composition, strength, porosity, burst yield, and stand off distance.

5. THE HYPOTHETICAL CASE OF DEFLECTING ASTEROID 25143 ITOKAWA

Near Earth asteroid 25143 Itokawa (Fujiwara, 2006) is a member of the Apollo asteroid dynamical family. It has an S-type reflectance spectrum, indicating a basaltic composition, and an ellipsoidal, potato-like shape, with dimensions of 535 m by 294 m by 209 m. Spacecraft observations indicate that it is a gravitationally bound rubble pile composed of fragments that vary in size over many orders of magnitude, and approximately 40% void space. It rotates in the plane of its long axis with a rotation period of 12 hours, well below a rate which would require strength to hold it together (Holsapple, 2007), so its rotation rate does not give a lower limit to its cohesive or tensile strength. Surface slopes in the range of 35--50 degrees indicate that the surface regolith does have some cohesive strength, of order or greater than granular materials observed on Earth. Its orbit crosses both that of Earth and Mars, although it does not currently pose an impact hazard to either planet. The asteroid was visited by the Japanese Aerospace Exploration Agency's Hayabusa mission in September 2005. A sample collection was attempted, and the capsule will be returned to Earth in 2010. The Hayabusa mission took extensive photographic, spectral, and LIDAR data in addition to the attempted sample return. This substantial set of observations makes 25143 Itokawa the best characterized sub-kilometer near Earth asteroid at this time.

We chose to model deflection scenarios for 25143 Itokawa because the asteroid is so well characterized. We begin with a set of two 2-D axisymmetric RAGE models of nuclear stand-off bursts. Ahrens and Harris (1994) estimate that a total yield of order 100 kt would be required to impart a change in velocity (δv) of 1 cm/s to a 1-km-diameter asteroid, given a geometrically optimal stand off distance, $h/R = 0.414$. We take their estimates as a starting point, and present the initial results of a model of a 100 kt burst 52 m away from the object on a line perpendicular to the plane of the shorter axes. This model, and one with a 100 kt burst 104 m away from the object along a line perpendicular to its long axis.

The source is approximated by a small aluminum sphere into which we directly add 100 kt of internal energy. We use the Ostro et al. (2004) shape model of 25143 Itokawa, obtained from Goldstone radio telescope data with 20 m resolution. The object is modeled with a minimum mesh resolution of 25 cm as porous SESAME Nevada Alluvium with an initial compressive strength of 0.2 bar, up to an assumed 1 kbar pressure to crush it completely, after which the material strength is set to zero.

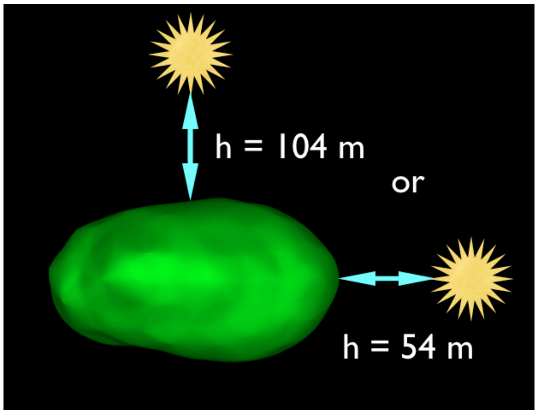

Fig. 3. The two initial configurations for the stand off burst models of 25143 Itokawa using the Ostro et al. (2004) shape model and Ahrens and Harris (1994) assumptions of a geometric optimum stand off distance.

The calculations are ongoing, using 60 2 GHz AMD Opteron processors each. The early results are encouraging. The source-facing side of the asteroid model is heated to a peak temperature of approximately 70,000 K, and heated above 1273 K, the temperature at which basalt begins to melt, in a thin outer layer that is likely under-resolved. This superheated mass has a velocity of approximately 10 m/s at early times.

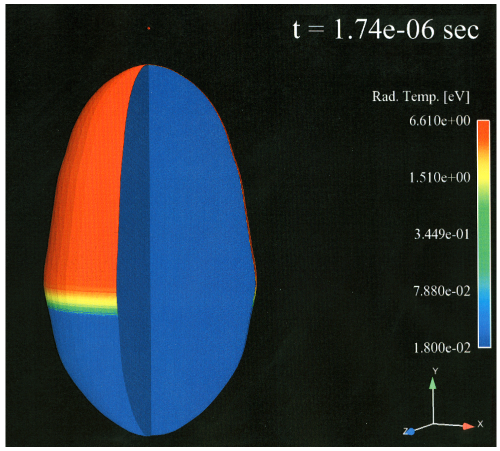

Fig. 4. A 270 degree projection of the target and exploding source, colored by temperature, shows the flash heating of the target surface at early times. This layer has a velocity of order 10 m/s at early times.

6. CONCLUSIONS AND FUTURE WORK

The initial results of the radiation hydrocode calculations presented here, and those presented by Clement et al. at this conference, demonstrate that it is possible to study the fast push deflection of potentially hazardous objects by nuclear burst using these computational tools. Initial RAGE models of the radiation and blast effects of a nuclear stand-off burst on a spherical 100-m-diameter object, and on a 500 m by 200 m by 200 m object composed of porous silicate regolith show flash heating of the blast-facing surface, mobilization of the ablated material, shock propagation through the target, and bulk object motion away from the blast. The 100 m simplest case model will be used in the future to conduct parameter studies of the effects of variations in target chemical and physical properties, and stand off distance from the burst. Further work with realistic asteroid shape models will be done to model specific hypothetical scenarios and explore the effects of asymmetries in target morphology on deflection processes.

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, rotation, 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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