LA-UR- 10-04495

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Intended for: International seminar on nuclear war and planetary emergencies, Erice Italy, 2010

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NATIONAL LABORATORY
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# Looking Before We Leap: An Ongoing, Quantitative Investigation of Asteroid and Comet Impact Hazard Mitigation

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***Abstract:***

There are many outstanding questions about the correct response to an asteroid or comet impact threat on Earth. Nuclear munitions are currently thought to be the most efficient method of delivering an impact-preventing impulse to a potentially hazardous object (PHO). However, there are major uncertainties about the response of PHOs to a nuclear burst, and the most appropriate ways to use nuclear munitions for hazard mitigation.

***Introduction:***

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. Impact craters were first documented by the cartographer Thomas Harriot in August of 1609 and confirmed in 1610 by Gallileo, who used the greek root for 'bowl' to describe circular depressions on the Moon without commenting on their origin. At the time these observations were significant for settling the contemporary debate between Averroe's interpretation of Aristotle's cosmology of geometric purity and the hypothesis originally by Plato, Plutarch, and others that the Moon was Earth-like in having a surface shaped by dynamic and ongoing processes[1]. Meteor showers and falls were known from prehistory, but meteorite origins were not scientifically accepted until the 1880s.

Asteroids were not discovered until 1801 when Giuseppe Piazzi discovered Ceres. It took another hundred years of improvement in telescope observations and geological field work until G. K. Gilbert and D. M. Barringer proposed an impact origin for lunar and terrestrial craters[2]. Gilbert's hypothesis was not widely accepted for many years. The chief criticism of the impact hypothesis was that nearly all observed impact craters are circular, whereas low-velocity impact experiments could only produce circular craters from nearly vertical impacts — suggesting the improbable result that all natural impacts were vertical. It took many more years until the mechanics of high-velocity impacts and their parallels to explosion cratering were better understood[3]. Two independent lines of research, the study of large explosions and high strain-rate geophysical responses to them during World Wars I and II, and the Cold War[4,5], and the observational and experimental work on impact cratering by Shoemaker, Gault, Ahrens, and others began to converge in the later half of the 20th century. A comprehensive understanding of impact processes and their context in the solar system was aided by observations and sample returns from Apollo and other space missions.

Impacts have occurred throughout history of our planetary system and indeed still occur now. The Tunguska event[6], the near miss of a similarly sized object in March 2009[7], collision of Comet Shoemaker-Levy 9 with Jupiter in 1994, and the August 2009 impact of a 500-m-diameter object on Jupiter[8] 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[9] has listed six objects hurtling between Earth and the Moon since 1991. 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 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 the Carancas event on 15 September 2007 in Alta Plana, Peru[10].

PHOs strike Earth with a frequency (commonly quoted as a function of object diameter) that is inversely correlated to their mass. There are more small objects so they 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[11] or 1:500 years in an urban area. The energy of the impact is simply the kinetic energy,

$$E = \frac{1}{2}mv^2.$$

The smallest events are seen as shooting stars. Several hundred metric tons of these small particles burn up in Earth's atmosphere every day[12]. Larger objects, up to perhaps 50 m in diameter, depending on composition, may burn up as they transit Earth's atmoshpere. 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)[13] and are analagous 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[14]. The minimum diameter is under debate. It was originally set to be comparable to the object that caused the Tunguska airburst[15], but recent calculations by Boslough and Crawford[16] indicate that the Tunguska impactor may have been as small as 30 m in diameter.

Asteroids are a diverse group of objects whose chemical composition varies 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%, and with the remainder made up of nickel-iron objects[17]. Small asteroids may be solid objects, indicated by a rotation rate that generate centripetal forces larger than the gravitational forces generated by a mass of that size, although this hypothesis is under debate[18]. Larger asteroids have been shattered repeatedly by collisions with other objects and so tend to be unconsolidated piles of gravitationally bound rubble.

There are a variety of current and ongoing surveys and missions that have the potential to significantly improve the planetary science community's understanding of near-earth and main belt objects. At the time of this writing, the Japan Aerospace Exploration Agency (JAXA) Hayabusa mission[19] sample return cannister has been retrieved, but the results have not been released. It is hoped that this cannister contains the first samples of a near-Earth asteroid collected in situ and returned to Earth. If so, it will provide ground truth for the comparison of asteroidal and meteoritite compositions, which will allow for better matches between the chemical compositions of laboratory samples and spectral measurements of basaltic asteroids. The NASA Dawn mission[20] is currently en route to 2011 and 2010 rendezvous with asteroids Vesta and Ceres where it will study the chemical properties of their surfaces and the bulk densities of the objects' interiors. 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 during its mission[21]. 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 24$^{th}$ 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[22].

Much less is known about comet nuclei. Determining the chemical composition of a comet nucleus is a complicated problem. Remote observations of the coma of a comet, formed by outgassing from the icy component of its nucleus under the influence of solar heat, yields only indirect information, (i.e., mother molecules of the ices are contaminated by molecular radicals and ions produced by solar ultraviolet radiation and chemical reactions in the coma). In addition, abundances in the coma are *not* the same as in the comet nucleus because the mixing ratio of chemicals (e.g., $CO/H_2O$) changes with heliocentric distance.

Space missions to comets have given the most reliable information. Among these missions are ESA's Giotto mission, the Russian's Vega 1 and Vega 2 missions, and

Japan's Sakigake and Suisei missions, all to Comet 1P/Halley; NASA's Deep Space 1 mission to Comet 19P/Borelly; NASA's Stardust mission to Comet 81P/Wild 2; and NASA's Deep Impact mission to Comet 9P/Tempel 1. Combining data from these missions and from groundbased observations of comets 1P/Halley, C/1995 O1 Hale-Bopp, and Hyakutake resulted in the best estimates for the composition and density of comet nuclei. More than 30 neutral cometary molecules have been identified that also exist in the interstellar medium. Scientists found that most chemical elements in comets are present in amounts consistent with solar system abundances, except for nitrogen, which is underabundant, and hydrogen, which is present only in amounts consistent with condensable species that can bind hydrogen (i.e., hydrogen molecules do not condense as ice because the temperature in comet nuclei is too high). ESA's Rosetta mission is the most likely to explore the interior of a comet. It was launched on 2 March 2004. After entering an orbit around Comet 67P/Churyumov-Gerasimenko in 2014, the spacecraft will release a small lander onto the nucleus and then spend the next two years orbiting the comet as it heads towards the Sun.

The most commonly quoted "impossible" hazard mitigation scenario is that of a previously unknown Oort cloud object. This object would have a diameter greater than 1 km, would be on a parabolic orbit with a high angle of inclination relative to the plane of the ecliptic (orbital plane of the solar system), would be discovered only after its first and only orbit brought it around the sun, and as a result we would have only months or weeks of response time remained before an impact. A comprehensive survey of the Kuiper belt and Oort cloud are unlikely to be completed for many years, but such surveys would both significantly add to our understanding of the solar system and minimize the statistical uncertainty on the threat of large impactors.

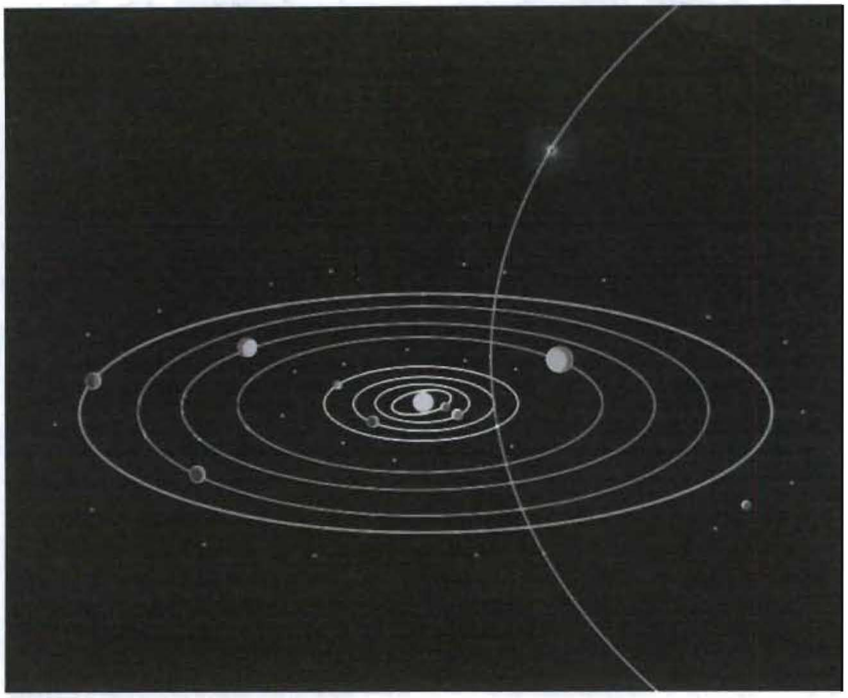

Fig. 1: A common hypothetical impact hazard scenario that would be technologically difficult to respond to would consist of a previously undiscovered Oort cloud object with a diameter larger than 1 km. This object would approach the inner solar system on a parabolic or hyperbolic orbit that is highly inclined to the plane of the ecliptic, and would intersect Earth's orbit in such a way that it would not be detectable until a few months before impact.

Minimizing the risk of damage to the Earth from a PHO or its fragments is known as hazard mitigation. It is accomplished through the disruption of a PHO and the dispersal of its fragments, or through modification of the PHO's orbit so that the threat to Earth is reduced or eliminated. Orbit modification can be accomplished in a variety of ways that fall into either "fast push" or "slow push" categories. Slow push methods include gravity tractors, albedo modification, and mass drivers[23], which are intended to provide a small change in velocity ($\Delta \mathbf{v}$) over time scales of years to decades and 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 delay, all of these proposed methods are untested and well beyond modern spacecraft 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 such as kinetic impactors[24], high explosives[25], and nuclear bursts[26] 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 10,000 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 a fast push deflection 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. Exploration of momentum coupling from the explosion to the PHO is part of the work presented here.

### *Methods*

Before we can say with certainty that an explosive yield $Y$ at height of burst $h < 0$ or depth of burial $h < 0$ will produce a change in velocity or dispersion of an object, we need to quantify how and where energy is deposited into the complicated media that may make up the object. We then need to understand how shock waves propagate through the system, what causes them to disrupt, and how long the gravitationally bound fragments of a disrupted system take to recombine.

We begin with a careful look at the coupling of energy from the mitigation technique to the PHO. Both explosive mitigation techniques and impacts can be thought of as inelastic collisions. The energy imparted to the PHO by the mitigation technique is known. For an impactor, this variable is the kinetic energy of the impactor. For a buried explosion, this variable is the yield of the explosion. For a stand-off explosion, it is the fraction of the explosion energy 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 explosion), $d\mathbf{a}$ 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.

However, kinetic energy is not conserved in any of these scenarios. Momentum imparted to the system of particles that make up the PHO may be estimated; however, the coefficient of restitution that would permit us to analytically calculate the velocity of the object or objects left after the mitigation impulse is a complicated function of the chemical and physical composition of the PHO system. We can model this response using numerical methods called hydrocodes to explore the effects of properties like equation of state, porosity, strength, and PHO shape on the system's response to an impulse. These models allow us to estimate the potential range of the coupling constant for different objects, and by extension, the change in velocities imparted to the components of a PHO system by a proposed mitigation technique, along with the range of uncertainties on those velocities, and the dynamical evolution of the post-mitigation system.

Various computational models separately track energy deposition from x-rays, gamma rays, or neutrons into different materials based on experimentally determined absorption cross-sections. These energy deposition processes are independent, so a piecemeal approach is physically reasonable. The well-known Monte Carlo particle transport simulation packages GEANT4[27] and MCNP[28] are used to estimate neutron or gamma-ray deposition. Once the location and amount of deposited energy is known, it can be sourced into the initial conditions of a radiation hydrocode model.

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 large relative to the object's properties (e.g., viscosity, strength, sound speed). Hydrocodes are widely used in planetary science to explore impact[29] and volcanic processes[30]. 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 light. Deflection or disruption of a PHO by nuclear burst is just such a problem. According to Glasstone and Dolan[4], 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 fraction 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). 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 appropriate for the materials encountered in the hazard mitigation problem is the SESAME library. SESAME is a temperature-based, tabular EOS library maintained by the Mechanics of Materials and Equations of State group at LANL. RAGE and SESAME have been through extensive verification and validation tests at every stage of their development.

Verification is the process of confirming that the physical models that the authors intend to include in the code are accurately implemented. It is done through comparisons of code results with analytical models of specific idealized physical processes. Validation is the process of comparing code model results to experiments of similar scenarios to establish that the physics implemented in the code is sufficient to model the scenario in question. RAGE model results have been compared with nearly 100 separate experiments and analytical models. Gittings et al. (2008)[31] document RAGE's performance on six separate verification problems, including spherical adiabatic compression, the Sod shock tube, Sedov blast wave, and the Marshak problem. Further detailed verification work is reported in Gisler (2005)[32], Kamm et al. (2002, 2000)[33,34].

Validation work has been conducted for many different physical situations including turbulent fluid flow experiments by Baltrusaitis et al. (1996)[35] and Zoldi (2002)[36], inertial confinement fusion (ICF) explored by Holmes et al. (1999)[37], Goldman et al. (2000)[38], Schappert et al. (2001)[39], Foster et al. (2002)[40], Wilde et al. (2000)[41], Parker et al. (2004)[42], Foster et al. (2005)[43], Lanier et al. (2006)[44], and Lanier et al.

(2007)[45]. Validation tests for physics of particular interest to hazard mitigation include Plesko et al. (submitted)[46] models of the Nakazawa et al. (2002)[47] study of shock propagation through basalt, comparisons of RAGE impact crater models with impact scaling relations from Holsapple (1993)[48] in Plesko (2009)[49], and comparisons of hydrocode models with laboratory-scale impact experiments in Pierazzo et al. (2008)[50]. Further validation work is ongoing at this time.

Constraint of energy coupling will draw heavily on experimental shock propagation work in relevant media, such as Housen and Holsapple (2003)[51] on impacts into porous media. It will draw on previous numerical studies of collisions of small solar system bodies and the energy required to disrupt them, $Q^*_D$, such as Benz and Asphaug (1999)[29] and Housen et al. (1999)[52], and on numerical techniques to approximate the relevant physics within current computational abilities, such as damage models[53], rigid body dynamics codes[54] and particle transport codes.

Energetic subsurface bursts are another method under consideration for impact-hazard mitigation. This technique has been popularized in the media, but still faces significant technical difficulties in the emplacement of the explosive device. There are two potential scenarios for the use of subsurface explosions to mitigate PHOs. First, if the source explosion were emplaced near the surface of the object ($h$~-10 m to -50 m) then the resultant shocks would preferentially eject material from the surface near the explosion and by conservation of momentum the remainder of the body will be given a significant force in the opposite direction. The goal of this type of intercept would be to impart a large enough velocity to the remaining object/fragments so that they would miss the Earth's orbit by a significant margin. The second subsurface method of mitigation would be to emplace the explosive source near the center of the object and independent of the composition of the PHO, the explosion would have enough power to significantly disrupt the entire body, leading to radial ejection velocities well above the escape velocity. Given a large enough explosion, here we consider energies of 1 – 10 megatons (Mt) TNT equivalent, the PHO would be fractured into smaller fragments with sufficient velocity to again miss the Earth's orbit by a significant margin. To begin we consider the second option, a centrally located explosion. We also build our computational models from simple to more complex by first considering uniform composition objects and then non-uniform, or "rubble pile" initial geometries. These rubble piles can have a very large range of actual internal compositions for which we have no actual data. We consider various rubble pile geometries as shown below. In this work we do not consider any political or engineering questions that might be involved in achieving the initial conditions assumed in these model hydrocode simulations.

***Results:***

We have explored energy deposition from stand-off bursts ($h > 0$) onto realistically shaped PHOs and the effects of internal object structure on the response of a PHO to a buried burst ($h < 0$). We find that our model results are physically reasonable and challenge previous assumptions about the response of PHOs to nuclear bursts.

In order to confirm our ability to study hazard mitigation with the tools available to us, we began with simplified models of nuclear deflection stand-off bursts at near Earth asteroid 25143 Itokawa. We chose to model deflection scenarios for asteroid Itokawa because the asteroid is so well characterized. 25143 Itokawa[19] 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. (See Fig. 2.) 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 that would require strength to hold it together[18]. 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 JAXA Hayabusa mission in September 2005. A sample collection was attempted and the capsule has been returned to Earth. 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 subkilometer near Earth asteroid at this time.

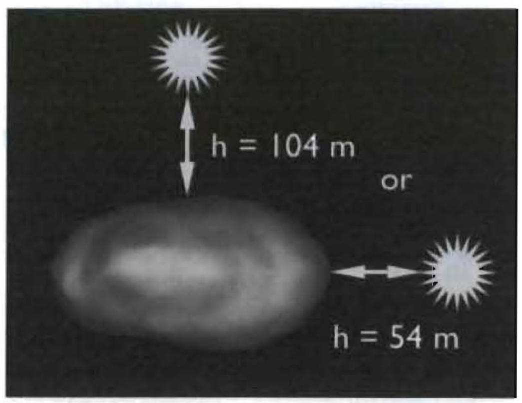


Fig. 2. Initial conditions for two different hypothetical nuclear deflection bursts at a target shaped similar to near-Earth asteroid 25143 Itokawa using the geometric optimum heights of burst, $h = 0.4r$.

We begin with a set of two two-dimensional (2-D) axisymmetric RAGE models of nuclear stand-off bursts. Ahrens and Harris (1994)[55] estimate that a total yield of order 100 kt would be required to impart a change in velocity ($\delta \mathbf{v}$) 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 10-kt burst, 52 m away from the object on a line perpendicular to the plane of the shorter axis. This model, and one with a 10-kt burst, 104 m away from the object along a line perpendicular to its long axis. We use the Ostro et al. (2004)[56] 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 (see Fig. 3).

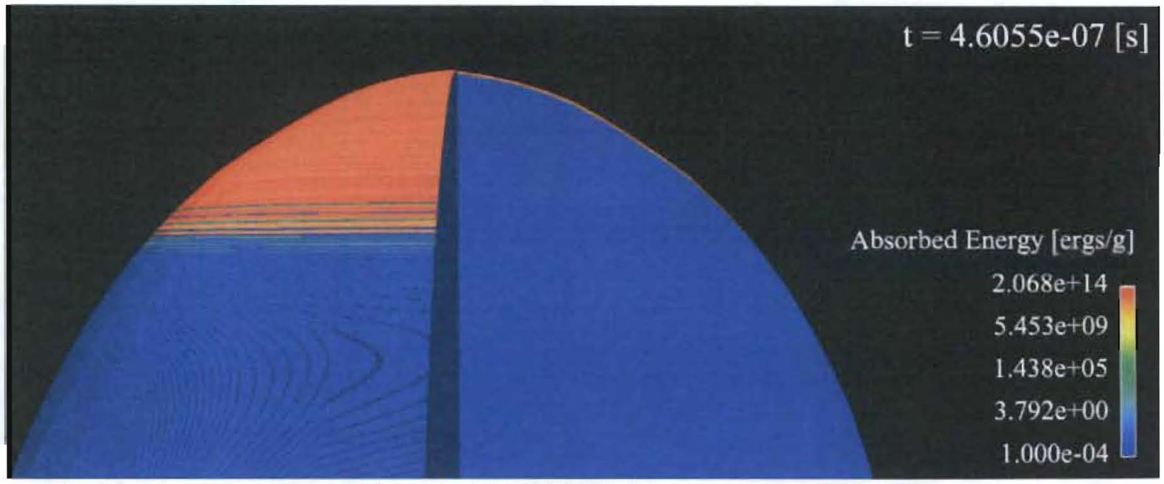


Fig. 3. Cut-away image of the Itokawa-like PHO target model, colored by absorbed energy after a 10-kt stand-off burst, 54 m off of the long axis of the object.

Fig. 4 demonstrates that approximately $8x10^{19}$ ergs are deposited into the target's near-surface by x-rays. $3x10^{19}$ grams of material are heated above the vaporization temperature of the target material. In this model, we see surface temperatures that are an order of magnitude higher than Ahrens and Harris anticipated from a burst yield that is an order of magnitude smaller than they recommended. This emphasizes the importance in validating the assumptions used in planning for any deflection scenario.

After the energy from the burst is deposited, the vaporized region of the target is expected to explosively decompress, pushing against the remaining solid portions of the PHO. This decompression sends a shock through the object. We are currently exploring the effects of the material properties of the target on both the initial deposition of energy, and on the post-deposition propagation of shocks through highly porous and heterogeneous media.

(a)

(b)

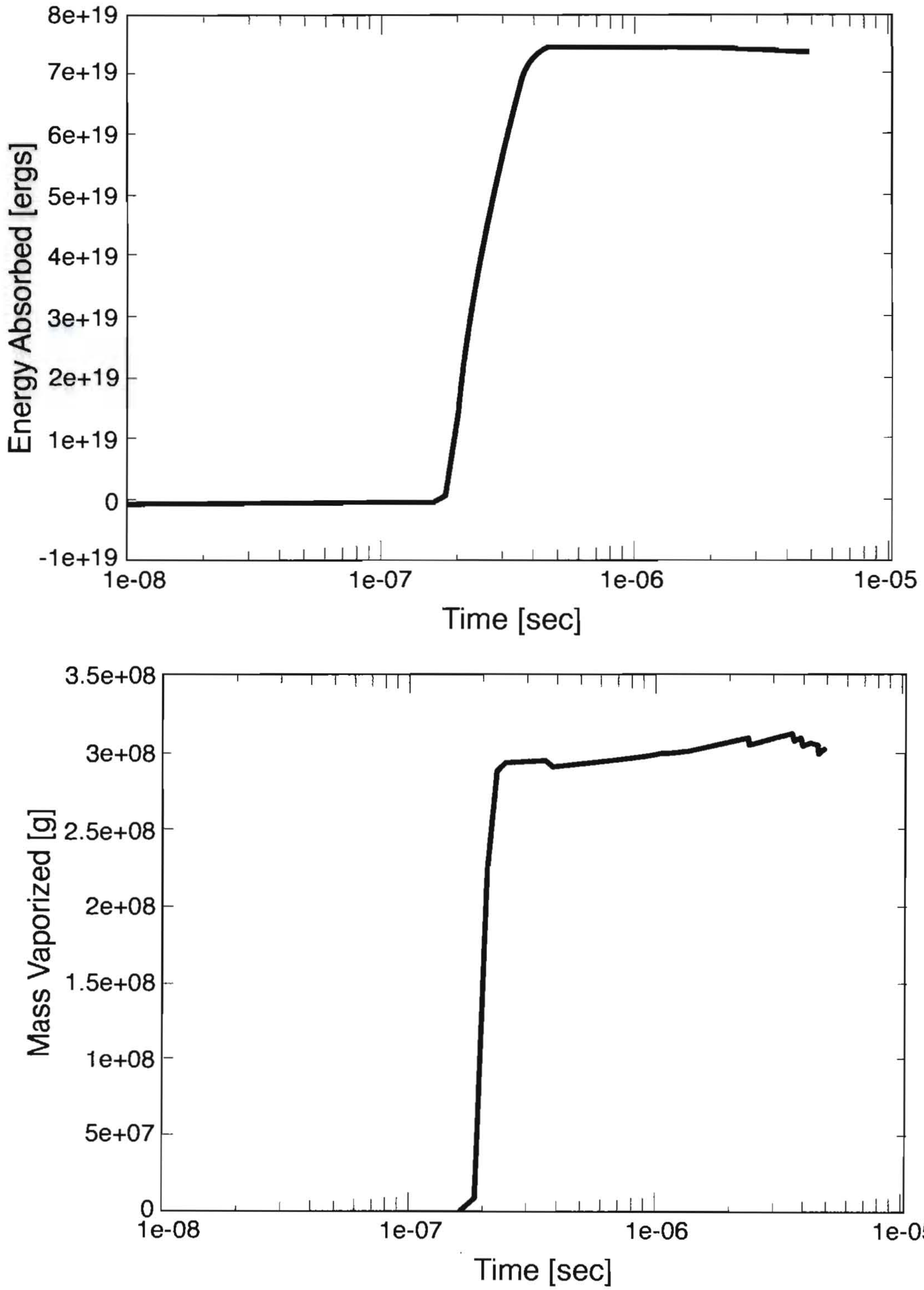


Fig. 4. (a) Modeled energy deposition by x-rays onto the target PHO and (b) the amount of PHO mass vaporized as a result.

In a parallel effort, we used the same RADAR shape model of asteroid Itokawa in RAGE hydrocode models of the shock-generated disruption of PHOs by subsurface, centrally located energetic bursts. We use known specific asteroid shape models in order to assess the consequences of various shapes and look for optimal emplacement of the source explosion. We will explore 2D and 3D models for the disruption by a large energy source at the center of such PHO models (1-10 Mt TNT equivalent), specifically for Itowaka (see Fig. 2), with future work on the Mars-crossing asteroid 6489 Golevka. We have conducted three sets of parameter studies to test the sensitivity of our models to the values of specific variables, over the plausible range of values those variables might take. First, we examined the response to explosive yield, $Y$, in the range 1 Mt $\leq Y \leq$ 10 Mt. Second, we explored the sensitivity to various parameters used by the Steinberg-Guinan strength model used for these buried burst models. Third, we explored the effects of an inhomogeneous rubble pile-like composition on PHO response.

We are interested in assessing the optimum depth of burial and energy required to essentially disrupt the PHO into much smaller objects many of which will not recollect and therefore mitigate the hazard. This work starts with a uniform composition model as shown in Fig. 5.

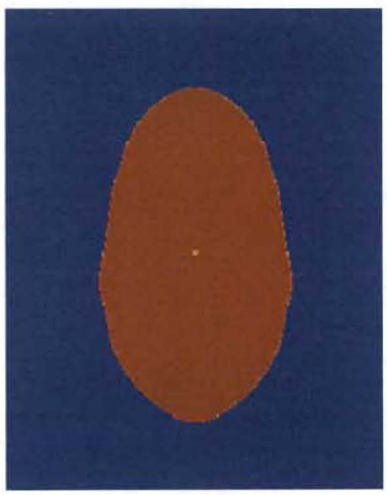

Fig. 5. An example of the initial conditions for a RAGE calculation of the Itowaka asteroid with a uniform iron composition and a central explosion.

In this example simulation we use a 1 Mt energy source with cylindrically symmetric geometry (2D). The RAGE hydrocode has been extensively validated for this type of strong shock, uniform composition model with detailed material properties, as described above. The result of this simulation is shown in Fig. 6 as a series of images from the time-dependant simulation.

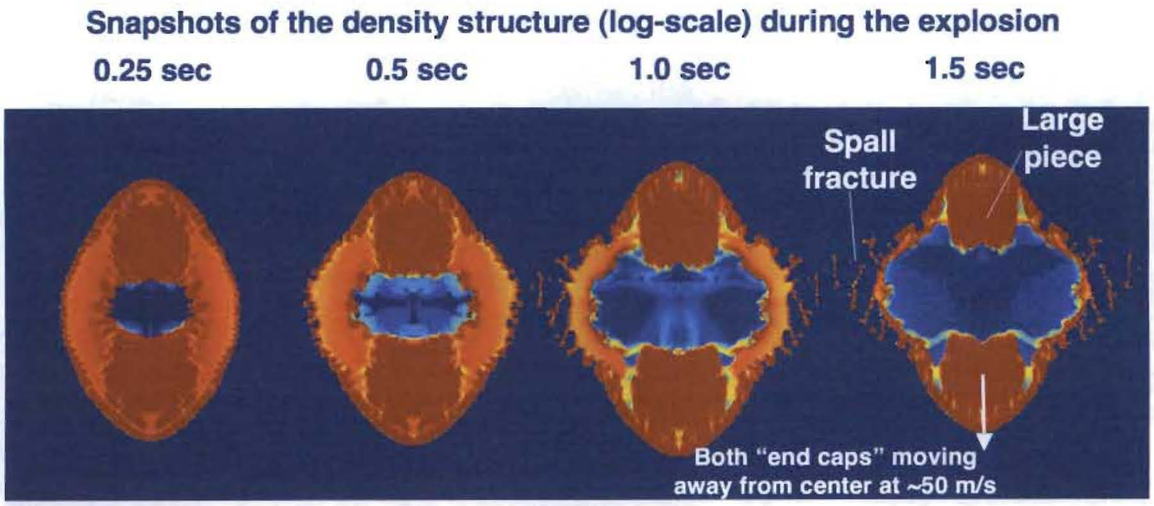


Fig. 6. An example of the RAGE calculation of the internal disruption of a model of the Itowaka asteroid by a massive explosion out to a time of 1.5 sec after the explosion. The model shows significant disruption of the modeled PHO.

We follow the time history of this simulation. The initial source energy is so large that it creates extremely high pressure surrounding the explosion. This high pressure leads to the formation of a strong shock wave that propagates spherically outwards leading to fracture of the surface of the object closest to the explosion. The high internal pressure continues to expand to the surface of the object, creating fractures planes and significant disruption of the object. Finally, we see that the high internal pressure results in the ejection of the large end-cap fragments with very high velocity. With an ejection velocity of 50 cm/s, the majority of the PHO mass would move two Earth-diameters away from the center of mass of the system after as little as one week. Given proper timing and orbital dynamics, we believe that this type of disruption scenario could effectively mitigate a PHO hazard. Further work is needed to confirm the accuracy of the mass-velocity distribution.

Next, we consider that same shape model of asteroid Itokawa but fill the shape with a rubble pile of solid rocks within a uniform background alluvium material. Each rock is composed of granite with appropriate strength models for both the rocks and the alluvium. The evolution of this RAGE simulation is shown in Fig. 7. In this simulation we have used a $Y = 10$ Mt TNT equivalent energy for the source. This larger yield leads to faster and more complete disruption of the object. The initial setup ( $t = 0$ sec) image shows the rubble pile composition of the PHO model filled with uniform 5 m radius rocks. The evolution of this disruption model is qualitatively different from that of the uniform composition object. Here the high pressure blast wave is able to shock more of the (weaker) PHO target material to a higher pressure, which results in vaporization of more material, and breakup of the non-vaporized mass into much smaller fragments.

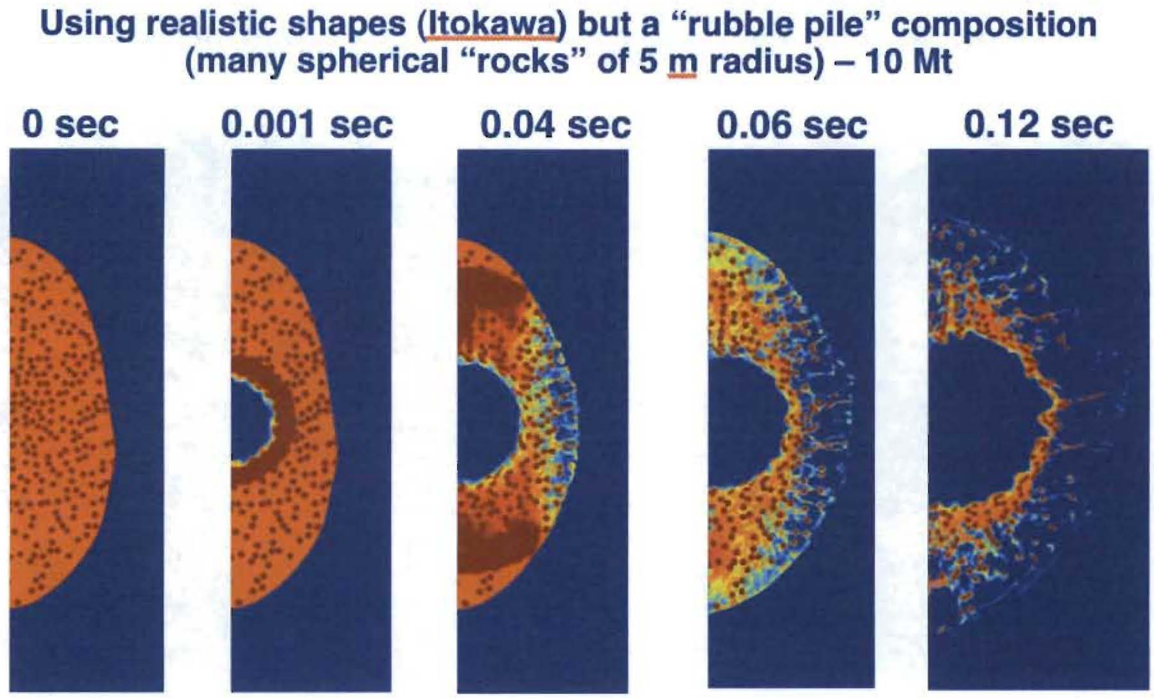


Fig. 7. An example of the RAGE calculation of the disruption of a non-uniform composition model of asteroid Itowaka by a massive explosion. Here we have used uniform size 5 m radius "rocks" to fill the shape contour. The model shows significant disruption of the "asteroid".

These simulations are examples of the variety of simulations we are pursuing in both 2D and 3D. Future models will include more realistic material physics and a variety of internal compositions.

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