Challenges of Deflecting an Asteroid or Comet Nucleus with a Nuclear Burst

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Abstract. There are many natural disasters that humanity has to deal with over time. These include earthquakes, tsunamis, hurricanes, floods, asteroid strikes, and so on. Some of these disasters occur slowly enough that some advance warning is possible for affected areas. In this case, the response is to evacuate the affected area and deal with the damage later. The Katrina and Rita hurricane evacuations on the U.S. Gulf Coast in 2005 demonstrated the chaos that can result from such a response. In contrast with other natural disasters, it is likely that an asteroid or comet nucleus on a collision course with Earth will be detected with enough warning time to possibly deflect it away. Thanks to Near-Earth Object (NEO) surveys, people are working towards a goal of cataloging at least 90% of all near-Earth objects with diameters larger than ~140 meters in the next fifteen years. The important question then, is how to mitigate the threat from an asteroid or comet nucleus found to be on a collision course with Earth. In this paper, we briefly review some possible deflection methods, describe their good and bad points, and then embark on a more detailed description of using nuclear munitions in a standoff mode to deflect the asteroid or comet nucleus before it can hit Earth.

Keywords: Impact Phenomena, Orbital Dynamics, Asteroids, Comets
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INTRODUCTION

Of all the potentially large-scale natural disasters, an impact from an asteroid or comet nucleus is the only one that is likely to be preventable. This prevention is in contrast to earthquakes, hurricanes, tsunami, floods, and volcanic eruptions where the most humanity can do is evacuate people from a threatened area and then deal with the damage afterwards. Large-scale evacuations can create chaos, as the evacuations for hurricanes Katrina and Rita demonstrated with the U.S. Gulf Coast. Although the impact frequency from a small asteroid is far smaller than the frequency of a hurricane (on the order of once every few centuries for a 50 to 100 meter object), the consequences of an impact can be far greater. For example, the kinetic energy of a 100-meter object entering the Earth's atmosphere at 10 km/s is approximately 20 Megatons. This amount is double the explosive energy of the Mike nuclear test that vaporized the island of Eugelab. The Tunguska event of June 30, 1908 destroyed about 2,000 square kilometers of Siberian forest (Steel 2008) and is currently believed to have been a stony meteor about 30 to 50 meters in diameter that exploded in the Earth's atmosphere with a force equivalent to 3 to 10 Megatons of energy. A bigger or faster asteroid would be even more devastating. As we just mentioned, with warning, it is possible for humanity to actively counter and divert the impactor.

CHARACTERIZING THE THREAT

For a long time, the threat of being hit by "rocks from space" was not appreciated, although there are recorded instances of objects, animals, and people being hit starting in the Middle Ages. The early 1900s (with the discovery

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of the Tunguska site by scientists in 1927) saw an increasing awareness that meteors can hit Earth. It was not until 1980 when Alvarez *et al*., (1980) put forth evidence that an asteroid roughly 10 km in diameter was responsible for the Cretaceous/Tertiary (K/T, now called the K-Pg boundary) extinction that people took seriously the possibility of climate change and mass extinctions from asteroids. Several surveys for near-Earth objects were sponsored and NASA reported the results of such surveys in 2007 (NASA, 2007). The goal of those surveys was to find 90% of all NEOs greater than 1 km in diameter. None of the >1 km size NEOs detected is a potentially hazardous object (PHO), which is defined as an object that can approach within 0.05 astronomical units (AU) of Earth's orbital path, or about 15 times the Earth-Moon distance. Since then, Congress has requested that NASA sponsor surveys that would find 90% of the PHOs greater than 140 m in diameter. At present, asteroid Apophis has been in the popular press as being predicted to have a very close approach in the next 20 to 50 years. As a result of public concern over false warnings in the press about possible asteroid collisions, astronomers came up with a risk scale for conveying information to the public. Binzel (2000) describes this scale, called the Torino scale, which runs from 0 (no consequence) to 10 (global devastation is certain). Since its inception, no object has rated more than a 1 for any length of time. Statistically, it is highly unlikely that any object will rise to more than a 3 on the Torino scale in the next 100 years. For the latest information on NEOs and their risk factors, we refer the reader to http://neo.jpl.nasa.gov/risk.

Although we have come a long ways since the Tunguska event of June 30, 1908, there is still much we do not know. Even when finished, planned surveys will still not be complete for objects smaller than 140 meters. Such an asteroid or comet nucleus would be large enough to wipe out an area from New York City to Washington, D.C. Objects smaller than about 140 meters will be difficult to detect with much advance warning simply because they are extremely faint except when they are close to Earth. Although we sent probes to several asteroids and comets, we only have detailed information for a few. We also do not have detailed knowledge of the internal structure of asteroids, especially ones of order 10 to 1000 meters in diameter. An asteroid's response to an impulsive energy burst --- whether it be high explosives, kinetic energy impactor, or nuclear burst --- will be sensitive to both the composition (ice, rock, rock/ice, or iron) and structure (monolithic piece, fractured, or rubble pile) of the body. While we may be able to determine at least the surface composition of a PHO in advance, we may not be able to determine the internal structure in advance. Any mitigation strategy must account for this uncertainty.

POTENTIAL THREATS

Suppose we detect a PHO headed towards us. Chances are, it will be in one of two categories. The first category of object likely to hit Earth would be a small, Tunguska-type body of order 10 to 100 meters in diameter. Because they are small, and hence very faint, they are difficult to detect with much warning time. It might be possible to deflect or destroy such a body in the future, but it would require the mitigation method to be ready and waiting for deployment on short notice. Even at 100 meters in diameter, the explosive energy would be about 100 Megatons and cause regional devastation. Such an object would not likely hit Earth more than once every few thousand years, and the chances of it hitting a populous area (out of the entire Earth) is even smaller (on the order of 1000 times smaller). The second category is that the PHO will be a larger object up to or greater than 1 km in size such as a comet nucleus headed towards us in a highly inclined orbit. If we are lucky, we will have several months to a couple of years lead-time. Although it did not come close to Earth, comet Kohoutek of 1973 would be an example of this class (Biermann, 1973). If we are not lucky, we will have very little advance warning, such as was the case for long-period comet IRAS-Araki-Alcock of 1983 (Watanabe, 1987; Sekanina, 1988). It was discovered on 27 April 1983 and closest approach was two weeks later on 11 May 1983 at a distance of 0.0312 AU (about 4.7 million km or10 times the distance of the Moon from the Earth).

Even if humanity had a deflection system ready, an object like comet IRAS-Araki-Alcock would be very difficult to deflect, especially because the nucleus was estimated to be 16x7x7 km (Sekanina, 1988). This size appears to be typical for long-period comets. Lest one become alarmed, the fraction of these objects (out of the total PHO population) is estimated to be at most a few percent. Further, only a small subset of these comet nuclei would be an impact threat. From the standpoint of likelihood of impact versus potentially large loss of life, objects that are about 1 km in diameter are the greatest threat (Morrison *et al.,* 2002; Chapman, 2004; Gritzner *et al*., 2006). Ironically, the threat from PHOs that are 1 km and larger is now known to be small. This proportion is largely the result of recent NEO surveys finding almost all of these objects that are believed to exist. None are known to be a threat at this time. Having said this, one should not ignore the potential threat. It would only take one impact to wipe out civilization.

MITIGATING THE THREAT

If we detect a PHO that is likely to hit us, we have several options besides doing nothing. The options fall into two broad categories. The first category is disruption and dispersal of the PHO into harmless fragments. While this scenario makes for entertaining Hollywood movies, in practice it would be extremely difficult to confirm that we did indeed disrupt the asteroid and disperse the fragments enough to be harmless. The second category is to deflect the PHO so that it misses the Earth, preferably with enough margin to avoid having the Earth's gravity modify the trajectory back into a threatening one again. For this scenario, we list the various deflection methods in Table 1, along with our assessment of their readiness, whether the method is fast impulse or slow push, and whether detailed information about the composition and structure of the PHO is needed for the deflection method to be effective. We note that all of these methods require information about the size, shape, and spin state of the PHO for maximum effectiveness.

Table 1. Different proposed mitigation strategies, their readiness, time needed for effectiveness, and whether detailed information about the structure and composition of the PHO is needed.

Method	Ready in ~10 years?	Fast/Slow	Detailed Information?
Pulsed Lasers	No	Slow	No
Asteroid tugboat	No	Slow	No
Gravity tractor	No	Slow	No
Enhanced Yarkovsky effect	No	Slow	No
Mass drivers	No	Slow	No
Focused solar reflectors	No	Slow	No
Surface detonation high explosives	Yes	Either	Yes
Kinetic energy impactor	Yes	Either	Yes
Surface or subsurface nuclear burst	Yes	Fast	Yes[1]
Standoff nuclear burst	Yes	Fast	Yes

[1]yes if the burst is small, no if high yield

Before turning to our main topic, we will comment on the various methods available for deflection. The "slow push" methods (the items marked "slow" in Table 1) are based on known physical principles but require considerable engineering effort to make them mature enough to consider deploying. Chemical explosives have a typical explosive energy of about 5 MJ/kg, implying that 1000 kg would have an energy of about 5 GJ. In contrast, if we consider a kinetic energy impactor of 1000 kg with an impact velocity of 30 km/s, the kinetic energy available is 900 GJ. This result shows that chemical explosives are generally less efficient than kinetic impactors (for the same mass), and that both are less efficient (per unit mass) than nuclear munitions (a 100 kt device would have an explosive energy of 4.19×10^5 GJ). We note that chemical explosives, kinetic impactors, and nuclear munitions are mature technologies and would be straightforward to mate to a booster rocket. The key question is how best to use a deflection method that will impart the needed deflection velocity ***without*** disrupting the PHO. This procedure is complicated by the fact that we will probably not know any more than the general properties of the PHO before we have to decide how to deflect it.

Although nuclear munitions are the most efficient means of delivering energy to deflect an asteroid and are technologically mature, they are fraught with problems, mostly political (see: Hanrahan, 2009) for some discussion of this). First, the Limited Test Ban Treaty of 1963, the Outer Space Treaty of 1967, and the Comprehensive Test Ban Treaty are all relevant to using nuclear munitions to deflect an asteroid. Specifically, the Limited Test Ban and Comprehensive Test Ban Treaties both prohibit a nuclear explosion in space. Clearly, high-level international agreements would be required to resolve this issue, and in our opinion, international cooperation for the deflection mission would be necessary. Besides treaty issues, there are people opposed to the idea of using any nuclear device for any reason.

There are two bad ideas that keep being brought up and we wish to deal with them those here. The first of these ideas is to use nuclear munitions to blow up an asteroid or comet nucleus (see http://www.universetoday.com/2008/07/27/bad-idea-blowing-up-asteroids-with-nuclear-missiles/ for a recent example). As we have already mentioned, we may not know enough about the asteroid or comet nucleus ahead of time to be sure to disrupt it into harmless fragments and disruption requires much more energy than just deflecting it. We feel that disrupting an asteroid should be considered a method of last resort. The second idea is to preposition orbital nuclear munitions. There are at least four reasons why we would not want to do this. First, orbital nuclear munitions are prohibited by the Outer Space Treaty. Secondly, nuclear munitions and rockets have a finite usable lifetime, so we would be sending payloads into orbit to maintain such a system. Third, there is minimal lead-time advantage to having a system in low-Earth orbit versus on the ground. Finally, an orbiting platform of nuclear munitions would be more likely to threaten people on Earth than an asteroid or comet nucleus. If a decision was made to use nuclear munitions to deflect a PHO, we would likely mate an existing nuclear assembly (or munitions) to a rocket on the ground. Another advantage to a ground-based launch system is that we can choose the most appropriate payload (chemical explosive, kinetic energy impactor, or nuclear munition) for the job and incorporate the latest reliable technology in the process.

Finally, although we will discuss standoff bursts, surface and subsurface explosions would increase the coupling of energy from the nuclear munition to the asteroid and make the countermeasure (nuclear or otherwise) more effective. However, this method requires a rendezvous mission and such missions require more time than an intercept (flyby) mission. This result underscores the fact that the available time for countermeasure deployment (lead-time) may be a crucial piece of information for deflection, particularly for small PHOs.

Our Topic: Deflection with a Nuclear Munition

The method we are most interested in is the use of nuclear munitions in a standoff mode to deflect a PHO. As mentioned earlier, we do not claim that this procedure is the only viable one. However, it is the only present method that is both technically feasible ***and*** capable of large amounts of energy for deflecting a PHO. Note that we consistently talk about deflection. While disruption of a PHO is possible, we are not convinced that we could disrupt a PHO into harmless pieces. Therefore, we consider disruption a method of last resort. In addition, the NASA (2007) white paper "Near-Earth Object Survey and Deflection Analysis of Alternatives" affirms deflection as the ***safest and most effective means*** of PHO impact prevention. It also calls for further studies of object deflection. Although technically viable, many questions remain as to the response of an asteroid or comet nucleus to a nuclear burst. Recent increases in computing power and scientific understanding of the physical properties of asteroids and comets make it possible to numerically simulate the response of these porous, nonspherical, and inhomogeneous bodies to strong shocks and radiation. Here we use the radiation-hydrocode RAGE (Gittings *et al.,* 2008) to explore energy coupling from a nuclear burst to a simplified PHO. We start with simple one-dimensional (1-D) and two-dimensional (2-D) models of material responses to variations in device yield, along with the composition and porosity of the PHO. We can calculate the neutron deposition of energy from a nuclear device into an asteroid using MCNP, a neutron/photon Monte-Carlo transport code (Brown *et al*., 2002). Once calculated, we can then input the neutron energy into RAGE to calculate the hydrodynamic response to the neutron energy deposition. The neutron energy is typically deposited into the asteroid in less than a microsecond, whereas the hydrodynamic response time of the asteroid is typically milliseconds or longer. This disparity in timescales makes it possible to accurately include both the x-ray and neutron energy deposition, which is important because there is no single code available that includes all of these effects.

Previous calculations of deflection by nuclear munitions (Ahrens and Harris 1994; Shafer *et al*., 1994; Simonenko *et al*., 1994; Solem and Snell, 1994; Dearborn *et al.,* 2007) either do not assume a standoff burst and/or do not account for the substantial porosity or internal composition variations from object to object. These properties may substantially affect how a PHO responds to a standoff nuclear burst (Holsapple, 2004a and 2004b). Plesko *et al.* (2008) and Bradley *et al*. (2009) have started calculations of the response of small solid-body asteroids to a nuclear burst, and we report on extensions of this work here. We do not include effects of porosity in this initial survey to keep the calculations simple and provide a reference point for comparison to other work and future calculations with porosity.

We use the RAGE radiation-hydrodynamics code (Gittings *et al.*, 2008) with radiation transport. For our initial studies, we use a 100-meter diameter spherical target that is of uniform composition. We have examined spheres of basalt, water ice, iron, and graphite to mimic the range of chemical compositions of likely asteroids and comet nuclei. We do not model the nuclear munition in detail. The energy is sourced into a small aluminum sphere over an arbitrary, but short time interval. This `device' is 20 meters away from the near surface of the target, which is the optimum standoff distance according to (Ahrens and Harris, 1994). To simulate the nuclear burst, we source in the desired amount of energy Because RAGE is not set up to handle a true vacuum, we use a low density (~3 x 10^{-8} g/cm^3) solar wind composition gas for the background. In Figure 1, we show the initial configuration of the target body (PHO) and nuclear munition.

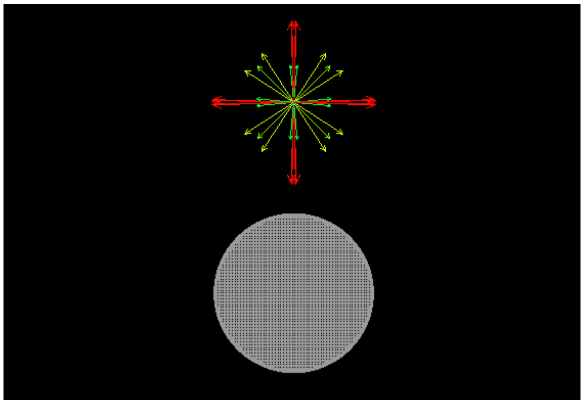


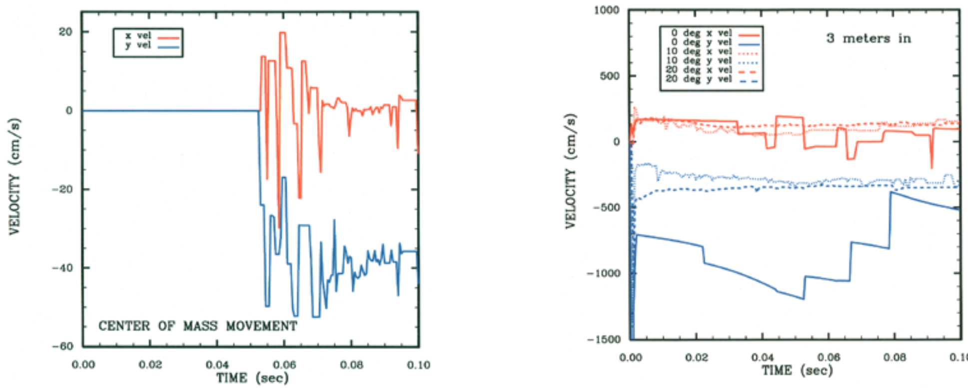
Figure 1. Initial configuration of the 100-meter diameter target body and nuclear munition (small dot, not to scale). The positive y-direction is down from the nuclear munition towards the target body and the positive x-direction is to the right in the figure. In our examples, the burst is either 20 or 70 meters from the target body surface.

For this parameter study, we consider solid spheres of pure basalt, water ice, iron, and graphite (at normal densities) to mimic the range of chemical compositions of likely asteroids and comet nuclei. All of these are simulated as uniform composition 100-m diameter spheres. We examine their response yields of 10, 100, and 1000 kilotons (kt). At present, we consider these sources to be blackbodies, which mean that most of the energy will be x-rays. We varied the standoff distance from 20 m to 70 m to investigate this effect. We ran the calculations to 0.1 seconds to obtain estimates of the ablated material and the deflection velocity imparted to the target.

At present, most of our results are for bursts of 10 and 100 kt. In Table 2, we show the densities and center of mass velocities of targets with different compositions deflected by bursts of 10 and 100 kt. The 100 kt burst produces a greater center of mass velocity, as does a lower initial density. We also ran calculations with bursts 70 m from a basalt sphere, and extra distance reduces the push by a factor of 5 to 10. Our calculation with the burst 70 m from the surface shows (see Figure 2) that the ablated material (originally 3 meters down) can expand off the surface with velocities up to 10 m/s (1000 cm/s). There is some radial component to the expansion, as the x-axis velocity can reach 1 m/s. Although it takes about 0.05 s for the center of mass to start moving, it reaches a velocity of 35 cm/s by 0.1 s. Note that the center of mass velocity is only 20 cm/s, showing that the motion of the center of the target does not necessarily correspond to the center of mass motion. From Ahrens and Harris (1992), moving an asteroid by 1 Earth radius requires a velocity deflection of ~7/*t* cm/s (where *t* is in years). Our 20 cm/s deflection would be adequate for a lead-time as short as 4 to 5 months. Moving the burst in to only 20 m above the "asteroid" surface makes it more effective. For example, a 100 kt burst 20 m from the "asteroid" surface imparts a center of mass velocity of about 190 cm/s. The velocity ratio (19.7/192 = 0.102) is almost exactly the ratio one would expect from the $1/r^2$ effect ($20^2/70^2$) of 0.082. Bursts of 1000 kt only 20 m from the target show significant disruption of the target by 0.1 s and such a burst would not be suitable for deflection.

Table 2. Center of mass velocities for targets that are 20 meters from a nuclear burst.

material	Density g/cm3	Target distance (m)	10 kt (cm/s)	100 kt (cm/s)
Water ice	0.998	20	80.9	577
graphite	2.25	20	7.2	206
basalt	2.868	20	7.6	192
basalt	2.868	70	1.7	19.7
iron	7.85	20	2.6	95.6



(a) **(b)**

Figure 2. In panel A, we show the velocity at the center of the target for a 100 m diameter basalt sphere exposed to a 100 kt burst 70 m from the surface. The shock hits the center about 0.05 s after the burst and the y-axis velocity reaches 35 cm/s by 0.1 seconds. In panel B, we show the expansion velocity of material near the surface of the basalt sphere. The expansion velocities can be as high as 10 m/s (1000 cm/s) and is concentrated in a cone with a half-angle of 30 degrees.

All of the targets mentioned so far have been spherical, but in reality, most asteroids and comet nuclei are not spherical. Asteroid 25143 Itokawa (Fukiwara *et al.,* 2006) is a well-studied example of such an object, with dimensions of 535x294x209 meters. Ostro (2004) produced a RADAR shape map of the asteroid that we will be using for radiation-hydrodynamic (with RAGE) and separate neutron (with MCNP) calculations of deflection by a nuclear burst. Asteroid Itokawa is an NEO, but it is not a PHO; we use it in our calculations simply because there are so much data for its size, shape, spin, and density. Figure 3 shows an example of an MCNP calculation where we use a 100-kt source with a neutron energy spectrum from the Trinity device. The source is off to the left of the Itokawa shape model and the yellow spots are the result of Monte-Carlo fluctuations caused by the small number of particles run (100,000) run in this test.

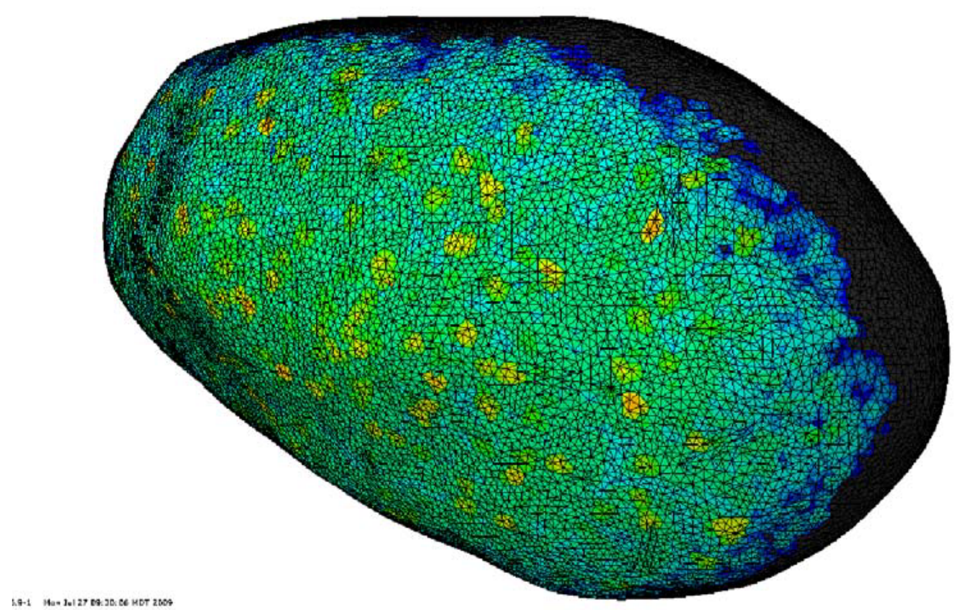


Figure 3. Example of neutron irradiation of an Itokawa shape asteroid model by a 100-kt device with a Trinity test neutron energy spectrum. The source is to the left of the page. The yellow spots are the result of Monte-Carlo noise.

CONCLUSIONS

In this paper, we describe the threat posed PHOs and mention how they are different from other natural disasters in two important respects. First, a large enough (greater than 1-km diameter) object has the potential to destroy civilization. At 10 km, a PHO would be roughly the size of the K/T impactor and would cause mass extinctions, including possibly that of humanity itself. Unlike other natural disasters where at best we can evacuate an affected area and deal with the damage afterwards, humanity has the potential to deflect a PHO before it collides with the Earth. There are many ways possible to accomplish this mitigation, but we feel that chemical explosives, kinetic energy impactors, and nuclear munitions are the only technologies that are readily available for the near term. Of these, we focus on nuclear munitions because they offer the most concentrated source of energy per unit mass. We must emphasize that deflection is our preferred option because we cannot reliably predict the fragmentation and dispersal of an asteroid.

We also describe our technical work on the possibility of using nuclear munitions for deflecting an asteroid or comet nucleus on a collision course with Earth. Our calculations of nuclear bursts with energies of 10, 100, and 1000 kt on spheres 100 m in diameter show that we can impart impulses of up over 500 cm/s. We also show that the composition of the target and distance of the burst from the target have considerable impact on the final center of mass velocity. However, these calculations do not yet include the material strength of the body, porosity, fractures, or irregularly shaped objects. We are starting to run calculations that use the shape of asteroid 25143 Itokawa as an example of an irregularly shaped object. Much work remains to be done and the ultimate goal of our project is to create a catalog of deflection simulations where we vary the distance, magnitude, and targeting of the burst from PHOs of different sizes, shapes, internal structure, and compositions (Huebner *et al*., 2009). This catalog would provide a playbook that decision-makers can use to guide the range of possible responses to a given PHO threat.

NOMENCLATURE

kt	=	kilotons of energy (4.18×10^{12} J or 4.18×10^{19} erg)
Mt	=	megatons of energy (4.18×10^{15} J or 4.18×10^{22} erg or 1000 kt)
NEO	=	a near-Earth object is an object whose orbit lies wholly or partially within the orbit of Mars. An alternate definition states that the orbit must lie at least partially between 0.983 and 1.3 AU.
PHO	=	a potentially hazardous object is an NEO whose orbit can come within 0.05 AU of the Earth's orbital path

ACRONYMS

NASA	-	National Aeronautics and Space Administration
NEO	-	near-Earth Object – an object whose orbit lies wholly or partially within the orbit of Mars (or that lie partly within 0.983 to 1.3 AU)
PHO	-	Potentially Hazardous Object – an object that can approach to within 0.05 AU of Earth's orbital path

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