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Challenges of Deflecting an Asteroid or Cometary 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, tsunami, hurricanes, floods, asteroid strikes, and so on. Many of these disasters occur slowly enough that some advance warning of which areas will be affected is possible. However, in almost all cases, the response is to evacuate the area to be affected and deal with the damage later. The evacuations for hurricanes Katrina and Rita on the U.S. Gulf Coast in 2005 demonstrated the chaos that can result. In contrast with other natural disasters, it is likely that an asteroid or cometary nucleus on a collision course with Earth is likely to be detected with enough warning time to possibly deflect it away from the collision course. 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 decade. The question is how to mitigate the threat from an asteroid or cometary nucleus found to be on a collision course. We briefly review some possible methods, describing their good and bad points, and then embark on a more detailed description of using a nuclear munition in standoff mode to deflect an asteroid or cometary nucleus before it can hit Earth.

Keywords: Impact Phenomena, Orbital Dynamics, Asteroids, Comets
PACS: (92.70.-j, 96.30.Cw. 96,30.Ys, 96.25.De)

INTRODUCTION

Of all the potentially large-scale natural disasters, an impact from an asteroid or cometary nucleus is the only one that is likely to be preventable. This is in contrast to earthquakes, hurricanes, tsunami, floods, and drought 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 United States' Gulf Coast. Although the frequency of impact from a small asteroid is far less (of order 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 about 20 Megatons. This 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 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 do something and avoid the impact.

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 1900's (with the discovery of the Tunguska site by scientists in 1924) saw an increasing awareness that Earth can be hit by meteorites. It was not until 1980 (Alverez et al. 1980) put forth evidence that an asteroid roughly 10 km in diameter was responsible for the Cretaceous/Tertiary (KT) extinction that people took the possibility of serious climate change and mass extinctions from asteroids seriously. Several surveys for near-Earth objects were sponsored and NASA has reported on the results of such surveys in 2007 (NASA 2007). The goal of those surveys was to find 90% of all NEO's greater than 1 km in diameter. None of the ones detected is a potentially hazardous object (PHO), defined as an object that can approach to within 0.05 astronomical units (AU), or about 15 times the Earth-Moon distance. Since then, Congress has requested that NASA sponsor surveys that would find 90% of the PHO's greater than 140 m in diameter. At present, two objects have been in the popular press as being predicted to have very close approaches in the next 20 to 50 years. As a result of public concern over "dire warnings" in the press about possible asteroid collisions that turned out not to be true, 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.

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 complete, planned surveys will still not have much completeness below about 140 meters. Such an asteroid or cometary nucleus would be big 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 cometary nuclei, we only have detailed information for Eros and Itokawa. We also do not have detailed knowledge of the internal structure of asteroids, especially ones of order 10 to 1000 meters in diameter. How an asteroid will respond to an impulsive energy burst --- whether it be high explosives, kinetic energy impactor, or nuclear burst --- will be sensitive to both the composition of the body (ice, rock, rock/ice, or iron) and the structure of the body (monolithic piece or "rubble pile". While we may be able to determine at least the surface composition of a PHO in advance, we will not be able to determine the internal structure in advance. This uncertainty will have to be considered by any mitigation strategy.

THE MOST LIKELY THREAT

Suppose we do detect a PHO headed towards us. Chances are, it will be in one of two categories. First, is that it will be a larger object – up to 1 km in size – that is a cometary nucleus headed towards us in a highly inclined orbit. If we are lucky, we will have 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. If we are not lucky, we will have very little lead time, such as was the case for Comet IRAS-Araki-Alcock of 1983. 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 – 10 times the distance of the Moon from the Earth). Even if humanity had a deflection system ready, an object like IRAS-Araki-Alcock would be very difficult to deflect. Lest one become alarmed, the fraction of these objects (out of the total PHO population) is estimated to be at most a few percent. The second category of object likely to hit Earth would be small, Tunguska-type bodies of order 10 to 100 meters in diameter. Because they are small --- and hence very faint --- they will be 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 destruction. Such an object would likely not hit Earth more than once every few thousand years, and the chances of it hitting a populous area (out of the entire Earth) is very small. From the standpoint of likelihood of impact versus potentially large loss of like, objects that about 1 km in diameter are the greatest threat (Morrison et al. 2002; Chapman 2004). Ironically, the threat from PHO's of order 1 km and larger is now known to be small. This is largely the result of recent NEO surveys finding almost all of these objects believed to exist. None are known to be a threat at this time.

MITIGATING THE THREAT

If we detect a PHO that is sufficiently likely to hit us that we choose to deal with it, we have several options. They fall in two broad categories. The first is disruption of the PHO into harmless fragments. While this makes for entertaining Hollywood movies, in practice it would be extremely difficult to confirm that we did indeed disrupt the asteroid. The other option is to deflect the PHO so that it misses the Earth, preferably with enough margin to avoid having the Earth modify the trajectory back to a threatening one again. With this said, 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 the methods need information about the size, shape, and rotation rate 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
Standoff nuclear burst	Yes	Fast	Yes

Our Topic: Deflection with a Nuclear Munition

The method we are most interested in is to use a nuclear munition in standoff mode to deflect a PHO. As mentioned earlier, we do not claim that this is the only viable method. 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 one 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" (NASA 2007) 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 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 and inhomogeneous bodies to strong shocks and radiation. Here we use the radiation-hydrocode RAGE to explore the coupling of the energy from a nuclear burst to a simplified PHO. We start with simple 1-D and 2-D models of material responses to variations in device yield, along with the composition and porosity of the PHO.

Previous calculations of deflection by nuclear munitions (Ahrens 1994, Schafer 1994, Simonenko 1994, Solem 1994, and Dearborn 2007) either do not assume a standoff burst and/or do not account for the substantial porosity or internal composition variations. These properties may substantially affect how a PHO responds to a standoff nuclear burst (Holsapple 2004). 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 use the RAGE radiation-hydrodynamics code (Gittings et al. 2008) with radiation transport. For our initial studies, we use a fiducial 100 meter 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 cometary nuclei. We do not model the nuclear munition in detail. The energy is sourced into a 50 cm diameter aluminum sphere over an arbitrary, but short (~5 microsec) time interval. This ``device" is 20 meters away from the near surface of the target, which is the optimum standoff distance according to (Ahrens 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.

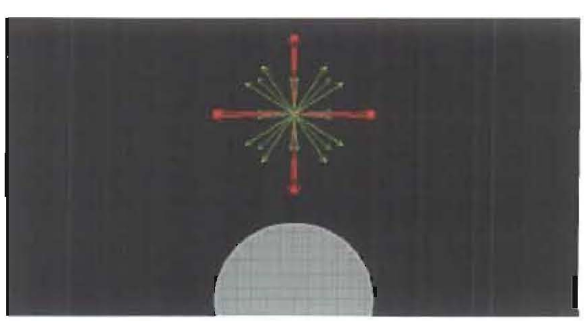

Figure 1. Initial configuration of the 100 meter diameter target body and nuclear muntion (small dot). The positive y direction is down from the nuclear munition towards the target body and the positive x direction is to the right in the figure.

For this parameter study, we consider solid spheres of pure basalt, water ice, iron, and graphite to mimic the range of chemical compositions of likely asteroids and cometary nuclei. All of these are simulated as uniform composition 100 m diameter spheres. We examine their response yields of 10, 100, and 1000 kt. At present, we consider these sources to be blackbodies, which means most of the energy will be X-rays. Finally, 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.

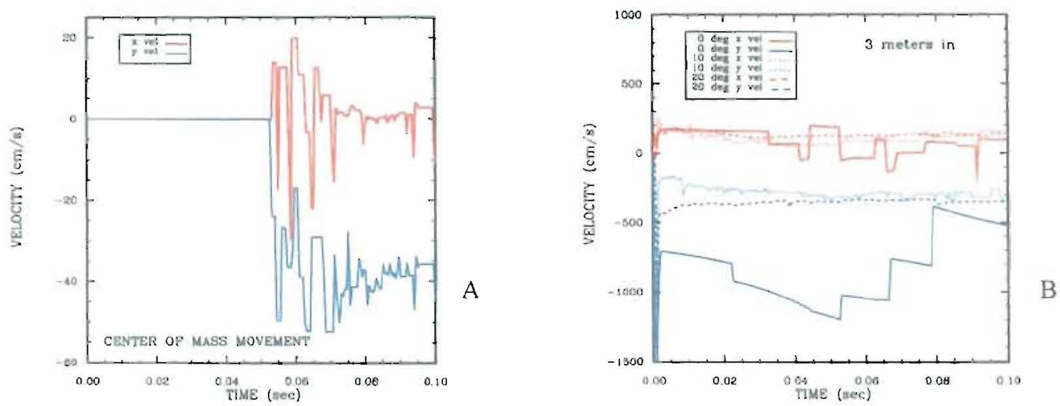

Figure 2. In panel A, we show the center of mass velocity for a 100 m diameter basalt sphere hit by a 100 kt burst 70 m from the surface. The y-axis velocity reaches 35 cm/s by 0.1 seconds after the burst. In panel B, we show the expansion velocity of material near the surface of the basalt sphere. The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

At present, most of our results are for bursts of 100 kt. Our run with the burst 70 m from the surface shows 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. 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 35 cm/s deflection would be adequate for a lead time as short as 3 months. Results for 100 kt 20 m from a basalt sphere. In contrast to the basalt sphere, a 100 kt burst 20 m from an ice sphere produces the expected result. The "asteroid" vaporizes.

CONCLUSIONS

In this paper, we describe our technical work on the possibility of using nuclear munitions for deflecting an asteroid or cometary 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 to 30 cm/s. However, these calculations do not yet include the material strength of the body, porosity, fractures, or irregularly shaped objects. We are starting calculations that use the shape of asteroid 25143 Itokawa as an example of an irregularly shaped object.

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)

ACRONYMS

Cretaceous/Tertiary (KT)
Cretaceous/Tertiary - (KT)
NASA - National Aeronautics and Space Administration
NEO - near-Earth Object
PHO - Potentially Hazardous Object

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