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When an Impactor is Not Enough: The Realistic Nuclear Option for Standoff Deflection

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When discovered sufficiently far in advance, impactors are the preferred deflection option for the more common, smaller asteroids. However, nuclear-explosive deflection may be essential for responding to the less common but more catastrophic large asteroids, or when the time to impact is short. A detailed understanding of the energy output of such devices and its deposition is a central part of estimating their deflection potential.

As an estimate of the deflection possible by the nuclear option, we report the prompt (250 μs) speed change induced by surface material vaporized by a nearby nuclear explosion. Using the impulse from the ablated, vaporized material imparted to the main body of the asteroid avoids uncertainty associated with additional ejecta (and impulse) that are affected by porosity. As such, our results represent a lower limit to the expected speed change. In the absence of porosity, longer hydrodynamic simulations have produced more momentum (speed change) by factors up to 3 or 4.

We have preformed simulations including the realistic output of gammas and neutrons, but for a typical nuclear explosive, their effects are negligible compared to x-rays. In addition to simulations using a realistic x-ray spectrum, a set of simulations using blackbody spectra of the same energy and delivered on the same time scales were done to demonstrate spectral sensitivity. The selected spectrum is not the best available, but represents a readily available system.

In the first figure, the blue line shows the prompt speed change for x-ray output of an extant nuclear explosive, scaled to 1 MT. The asteroid is modeled as a 560 m SiO_2 sphere with density of 0.98 g/cc for a total mass about 50% above that estimated for Bennu. This source was applied at distances between 50 and 1000 meters, resulting in speed changes between 1.5 and 6.6 cm/s. Again, the 1.5 cm/s obtained for a 1 km height of burst is a lower limit of the speed change, but even so, corresponds to the momentum of a 67 ton mass impacting at 20 km/s. For a beta of 5, the impactor mass is reduced to 13 tons, but such a beta is likely only for porosities where the nuclear impulse will also be substantially augmented. The spectrum selected for this example is far from the best available, but represents a readily available system.

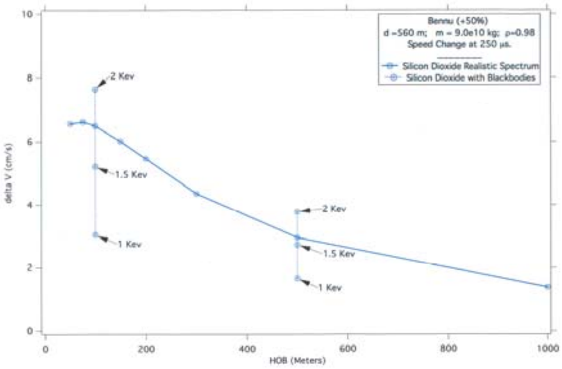

Figure 1: Comparison of a realistic output spectrum compared to black body spectra with the same energy.

Returning to the subject of spectral sensitivity, the vertical dotted lines at 100 m and 500 m height-of-burst (HOB) show results for 1 MT. of x-rays at different black body temperatures. Note that for the same total energy, the spectrum (black body temperature) makes a large difference. Note also that the black body temperature required to achieve the same effect changes with distance. This shows that the actual output is not a blackbody, and demonstrates the spectral sensitivity. Because nuclear explosives differ considerably, the impulse imparted by a nuclear explosive is not simply characterized by the yield. There are systems for which the impulse per kiloton are many times that found for this spectrum, so in this way too, these results represent a lower bound.

The spectral sensitivity is a consequence of differences in depth to which the radiation energy penetrates, and the fraction of energy reradiated (lost). The low-energy portion of the spectrum is deposited in a very thin layer, heating it sufficiently that significant energy is lost through reradiation. Thin hot layers are also inefficient at producing momentum (per unit energy) as expansion speeds increase only with the square root of the temperature. The second figure shows that for high fluxes (100 m HOB), black bodies between 1 and 2 Kev reradiate 45% to 75% of the energy impinging on the asteroid.

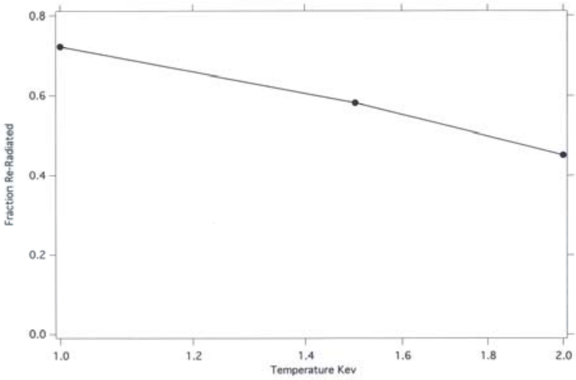

Figure 2: The fraction of the blackbody energy reradiated from the model at 100 m HOB for temperatures between 1 and 2 Kev.

We have repeated the simulations described above with different compositions, densities, and sizes, to begin defining those asteroid characteristics that are important to the deflection community. The third figure shows the impulse resulting from a realistic spectrum on bodies composed of a hydrated forsterite, pure SiO_2, granite, ice, and a mixture of water and sand.

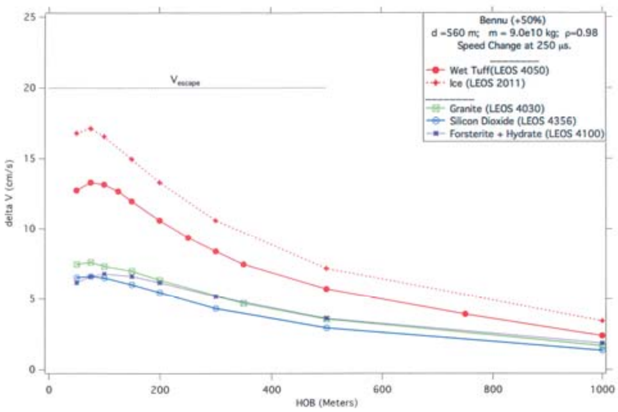

Figure 3: The speed change versus height of burst for a realistic x-ray output and different compositions.

All of the rocky materials show similar behavior. For elements like (O, Si, Mg, and Al) the location of the K edges are in the range 1 to 3 Kev, and only x-rays well above these energies penetrate to provide substantial momentum deposition. The presence of substantial iron will raise the photon energy required for penetration making the iron abundance important for characterization. In contrast, enhanced impulses are seen when water or ices are present as volatiles (not bound in a high temperature hydrate).

To test the scaling of these results, individual models were run with larger (1 km) and smaller (0.5 km) asteroid sizes, higher (2.6 g/cc) and lower (0.958 g/cc) densities, and two compositions (pure SiO2, and SiO2 + water). This was all done for 100 m HOB, and the same 1 MT. spectrum. When only the density changes, the scaling applied was just the mass difference. When the size changes, the impulse was scaled by the fraction of energy intercepted. In the tables below, the speed change found from the simulation is in the column labled "dV", while the scaled speed is in the column "dV-Scaled".

Composition: SiO_2

Density (g/cc)	Diameter (km)	dV (cm/s)	dV-Scaled (cm/s)
2.60	1.0	0.56	-
1.91	1.0	0.77	0.76
0.98	0.56	6.5	6.2

Composition: $SiO_2 + H_2O$

Density (g/cc)	Diameter (km)	dV (cm/s)	dV-Scaled (cm/s)
1.91	1.0	1.64	-
0.98	0.56	13.5	13.2
0.958	0.50	19.4	18.8

Looking at the SiO_2 bodies, the prompt speed change at full density (2.6 g/cc) for a 1-km sphere was a bit over 0.5 cm/s. Lowering the density to 1.91 g/cc reduced the mass, and increased the speed, as expected for the lower mass. This required the impulse to be the same despite the lower density. This is expected because the opacity limiting x-ray penetration can be measured in g/cm^2, so at a lower density, the x-rays penetrate farther, and heat the same mass. Lowering the size to 0.56 km, and the density to below 1 g/cc reduced the mass by a factor of 17. It also reduced the fraction of source energy impingent on the body from about 22% to 16.2%. Simply scaling the 1 km full-density model with those factors increases the 0.56 cm/s result for the full density model to 6.2 cm/s (as compared to 6.5 cm/s from the simulation).

As shown in Figure 3, simply changing the rocky (mid-z) materials results in similar speed changes (+/- 10%). This suggests simple scaling by mass and energy intercepted can be moderately well estimated for such composition changes. Composition changes that add a volatile like water will result in substantially increased impulse, and require separate simulations (as shown in the second table).

Finally, with these determinations of the minimum speed change expected from nuclear explosives, we examine deflection options as a function the range of sizes and times-to-impact. Readily available yields are sufficient for kilometer-sized objects, and the HOB can be modified to tune the deflection magnitude for smaller (<1 km) bodies. Currently existing nuclear explosives are adequate for essentially all NEOs, providing they are discovered early enough.

As stated in the beginning, impactors will be preferred when possible. In the fourth figure, a nominal curve shows the deflection of a 10-ton body impacting at 20 km/s. Also shown are cases with 10x and 1/10th the nominal momentum. Larger asteroids become too massive for impactors, and the nuclear option is the only alternative to the most catastrophic (though rarer) impacts.

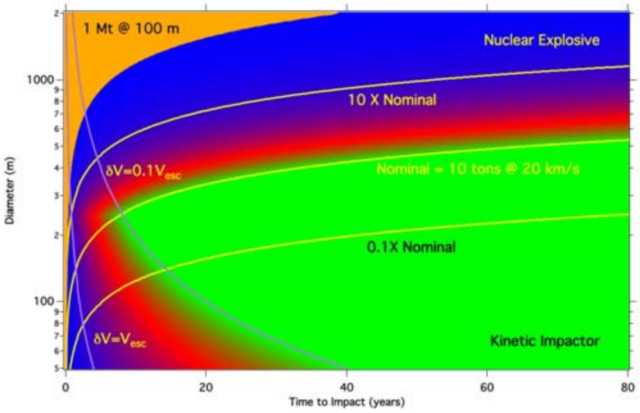

Figure 4: An illustration of asteroid sizes and times to impact suggesting where impactors will be adequate and where they are not.

For short times to impact, the required speed change becomes significant compared to the escape velocity. Any body that is not strongly cohesive is at risk of fragmenting (regardless of the impulse source). Fragmentation creates a debris field through which the earth passes, and in such a case, it is important that the fragments are dispersed with a speed such that the cloud is highly tenuous. Here again the nuclear option has greater capability than a kinetic impactor.

As a final note indicating future research, the examples shown here are idealized, with the x-ray absorption occurring only on a smooth surface. A realistic surface will include irregularities that can enhance the effectiveness of low energy x-rays by increasing the mass (surface area) exposed to energy and reducing the energy lost to reradiation. To illustrate this, consider a surface that is flat, and one that has notches of width r and depth d. The surface area illuminated depends on the aspect ratio of the notches (d/r) and the angle of illumination.

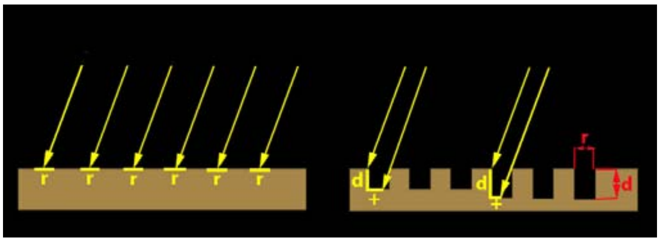

Figure 5: Comparison of area illuminated on a flat surface, and an irregular surface.

Such surface roughness (where r >penetration depth) increase the mass exposed to the x-ray energy. As a result the temperature, and reradiation of a surface element is reduced, and the reradiation that does occur is partially absorbed in other portions of the notch.

A quick look at this effect for irradiation just off normal shows substantial enhancements are possible from surface irregularity.

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