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Blow-off momentum from melt and vapor in nuclear deflection scenarios[☆], [☆☆]

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ABSTRACT

For Earth-impacting objects that are large in size or have short warning times nuclear explosives are an effective threat mitigation response. Nuclear-based deflection works by means of conservation of momentum: as material is heated by incoming photons and neutrons it is ejected from the body which imparts momentum to the remaining mass of the asteroid. Predicting the complete response of a particular object is difficult, since the ejecta size and velocity distributions rely heavily on the unknown, complicated internal structure of the body. However, lower bounds on the blow-off momentum can be estimated using the melted and vaporized surface material. In this paper, we model the response of a one-dimensional SiO_2 surface to monoenergetic soft X-ray, hard X-ray and neutron sources using Arbitrary Lagrangian–Eulerian radiation/hydrodynamic simulations. Errors in the blow-off momentum due to our hydrodynamic mesh resolution are quantified and inform zone sizing that balances numerical discretization error with computational efficiency. We explore deposited energy densities ranging from 1.1 to 200 times the melt energy density for SiO_2, and develop an approximate relation that gives the mesh resolution needed for a desired percent error in the blow-off momentum as a function of deposited energy density and melt depth. Using these mesh constraints, the response of our one-dimensional SiO_2 surface to the energy sources is simulated, and lower bounds are placed on the melt/vapor blow-off momentum as a function of deposited energy density and source energy type.

1. Introduction and background

Large asteroid and comet collisions with Earth represent a low-probability but potentially high-consequence threat. The devastation from a collision with an asteroid or comet ranges from localized disasters to global extinction. Orbit tracking predicts that hundreds of Near-Earth Objects (NEOs) will come within 20 lunar distances of the Earth over the next century. More than two dozen of these NEOs will have diameters greater than 150 m (1/10 mile).[1]

While a suite of methods have been proposed to deflect NEOs, the most effective means of diverting a body is to use nuclear explosives, which are 10–100 times more effective than non-nuclear alternatives [1]. For scenarios in

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[1] Based on data obtained from the IAU Minor Planet Center, http://www.minorplanetcenter.net/.

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which there is little warning time before impact or if the NEO is large, nuclear explosives may be the only option. Therefore, understanding precisely how these objects respond to nuclear explosions is critical.

In this paper, the lower bounds on the NEO blow-off momentum resulting from a nuclear explosion are explored by coupling energy to NEO-like material. As an initial idealization, we model the NEO as a one-dimensional column of SiO_2 to study how energy couples to the material using a particle transport code, and how the material responds using hydrodynamic simulations. We explore the minimum amount of momentum transferred as a function of deposited energy density and source type, and quantify the blowoff momentum as a function of mesh resolution. The high melting and vaporization temperatures of SiO_2 provide a reasonable lower limit on momentum transfer for a generic NEO scenario. Further studies with more representative compositions will follow at later time.

2. Energy coupling

A significant fraction of the energy output in a nuclear detonation comes in the form of X-rays and neutrons. We investigate the one-dimensional energy deposition on SiO_2 from three monoenergetic sources: 10 keV soft X-rays, 100 keV hard X-rays and 2.45 MeV neutrons. Realistically, X-rays and neutrons take a finite time to penetrate the surface and interact with the material. However, the timescales associated with energy deposition are extremely short compared to those for hydrodynamic motion, so we neglect this shorter timescale and instead couple the energy directly to the material before simulating the surface response.

According to the Beer–Lambert Law, the probability of a mono-energetic photon or neutron interaction within a homogeneous material decreases exponentially with path length. This simple exponential attenuation law provides a rough guideline for the behavior of energy in material. In reality, scatter and capture reactions produce energy deposition profiles that are more complex. Here, we assume that the energy deposition profile decays exponentially with path length, characterized by the penetration depth λ_d at which a fraction $(1-1/e)$ of the total energy has been deposited:

$$\epsilon_{\text{dep}}(r)=\epsilon_0 \exp\left(-\frac{R-r}{\lambda_d}\right), \tag{1}$$

where ϵ_0 is the deposited energy density at the surface, R is the radius of the NEO, and $R-r$ is the depth relative to the NEO surface. For a spherical body, the deposited energy density ϵ_0 is related the total flux of the source by

$$\epsilon_0=\frac{\eta_Y Y}{4\pi d^2 \lambda_d}, \tag{2}$$

where η_Y is the yield coupling efficiency (i.e. the fraction of total incident energy deposited), Y is the total yield of the monoenergetic source type into 4π steradians, and d is the distance between the source and the surface of the body.

Table 1 summarizes the values of λ_d and η_y as determined using MCNP6 simulations, a Monte Carlo N-particle transport code developed by the Los Alamos National Laboratory [2] with the ENDF/B-VII.1 US Evaluated Nuclear Data Library [3].

Table 1
Penetration depths λ_d and yield coupling efficiencies η_Y as determined by MCNP6 simulations for three source types: a soft X-ray source, a hard X-ray source, and a neutron source. The penetration depth λ_d represents the depth at which $\eta_Y(1-1/e)$ fraction of the energy has been deposited. The energy coupling efficiency η_Y is the fraction of the total incident energy that is deposited in the material. The neutron source has a yield coupling efficiency greater than one due to the additional energy released in neutron capture reactions. The ENDF/B-VII.1 US Evaluated Nuclear Data Library is used for the nuclear cross sections [3].

Energy type	λ_d (cm)	η_Y
10 keV	0.02	1.0
100 keV	3.87	0.82
2.45 MeV	45	1.7

We find neutrons to be the most effective source type in this study because, at the relevant energies, they penetrate deeper into the material than the X-rays. For the same deposited yield, a neutron source heats more material to a lower temperature, while an X-ray source heats less material to a higher temperature. In an exponentially decaying energy profile at energies sufficient to melt material, the mass melted scales as

$$m \propto \lambda_d. \tag{3}$$

Using the momentum and kinetic energy scalings,

$$p=mv, \tag{4}$$

$$v \propto \sqrt{\epsilon_0}, \tag{5}$$

and Eq. (2), it can be shown that the blow-off momentum scales as

$$p \propto \lambda_d \sqrt{\epsilon_0} \propto \sqrt{\lambda_d \eta_Y Y}. \tag{6}$$

This demonstrates that, for identical yields Y and for deposited surface energy densities ϵ_0 sufficient to melt material, energy sources with larger penetration depths λ_d and higher yield coupling efficiencies η_Y (e.g. the neutrons) are a more efficient momentum source since they penetrate deeper into the material and distribute their energy over a larger mass.

As previously mentioned, for an energy type to be effective it must heat a material above its melting point. We define the melt energy density, ϵ_{melt}, as the amount of energy per cubic centimeter needed to heat a material from an initial temperature of 100 K (a temperature characteristic of NEOs) to the melting temperature plus the enthalpy of fusion. For SiO_2 at reference density 2.65 g/cc the melt energy density is $\epsilon_{\text{melt}} \sim 5.1$ kJ/cc [4]. In an exponentially decaying profile, the depth of material melted is

$$z_{\text{melt}}=\lambda_d \ln \frac{\epsilon_0}{\epsilon_{\text{melt}}}. \tag{7}$$

In Fig. 1, we plot the melt depth as a function of the flux for each of the three source energy types. The curve for each source type rises above zero at the flux needed to reach the melt energy density at the surface (by substituting ϵ_{melt} for