NEOSHIELD STUDY OF HYPERVELOCITY IMPACTS INTO SMALL BODIES: SIMULATING THE FATE OF EJECTA.

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Introduction: Asteroids and comets collide with the Earth, profoundly influencing life on the planet with stochastic impact events that may occur over timescales of millions of years. It has been estimated that about every year, asteroids measuring 4 meters across enter Earth's atmosphere and detonate [1], and that asteroids of 100 meters tend to impact the Earth every 5,000 years. On average, collisions with 4-kilometer asteroids are occurring about every 13 million years [2]. In 2005, a United States Congressional mandate called for NASA to detect, by 2020, 90 percent of Near-Earth Objects (NEOs) with diameters of 140 meters or greater [3].

As sky surveys are performed, and detection strategies are developed, for discovering small bodies that may be on trajectories to collide with the Earth, it is prudent to concurrently be developing and refining mitigation strategies, including those that could alter the paths of hazardous objects. (Strategies that do not involve affecting a hazardous object's path would include civil defense approaches.) However, any discussion of efforts to deviate the path hazardous Near-Earth Objects (NEOs) must incorporate an analysis of the makeup of the body. The assumption that asteroid surfaces consist of granular material is based on the results of several observations, including confirmation by space missions that have visited asteroids in the last few decades [5,6]. It appears that all encountered asteroids thus far are covered with some sort of granular material, usually referred to as "regolith." To date, this includes a large range in asteroid sizes, from the largest one visited, by the Dawn spacecraft, the main belt asteroid (4) Vesta, which measures about 500 kilometers across, to the smallest one, sampled by the Hayabusa mission, the NEO (25143) Itokawa, which measures about 500 meters across [7,8]. Thermal infrared observations also support the idea that most asteroids are covered with regolith, given their preferentially low thermal inertia [9].

One of the four main types of mitigation strategies explored by the United States' National Research Council's (NRC) "Committee to Review Near-Earth Object Surveys and Mitigation Strategies" involves using an impactor spacecraft to deflect an NEO from its path by crashing into it at speeds of up to 10 km s^{-1} or more [9]. The three other strategies outlined by the NRC include detonations on or beneath the asteroid surface (nuclear and non-nuclear), gravitational tractors, and broad civil defense approaches. The NEOShield Project aims to design a general NEO defense strategy based upon momentum transfer via kinetic impact [10]. Begun in 2012, the NEOShield Project is being funded for 3.5 years by the European Commission in its FP7 program. It is a, primarily, but not exclusively, European consortium of research institutions that aims to analyze promising mitigation options and provide solutions to the critical scientific and technical obstacles involved in confronting threats posed by the small bodies in the neighborhood of Earth's orbit. Here, we study numerically some of the details involved in a kinetic impactor approach to NEO threat mitigation as part of a specific work package of NEOShield.

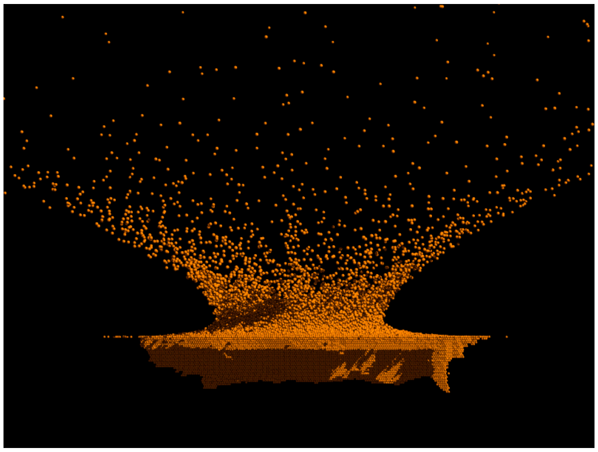

Figure 1: Initial phase of a numerical simulation involving a 400 kg, 1 g cm^{-3} spherical projectile impacting a target, 300 m in diameter, at 10 km s^{-1}. Since the target body is large compared to projectile and resulting crater size, only a region measuring 30 m across is shown in the image.

Numerical Method: We perform the majority of a given impact simulation using `PKDGRAV`, a parallel N-body gravity tree code [11] adapted for particle collisions [12,13]. A soft-sphere collisional routine was added recently [14]; with this option, particle contacts can last many timesteps, with reaction forces dependent on the degree of overlap (a proxy for surface deformation) and contact history—this is appropriate for dense and/or near-static granular systems. The code uses a 2nd-order leapfrog integrator, with accelerations due to gravity and contact forces recomputed each step. In the spring/dash-pot model used in `PKDGRAV`'s soft-sphere implementation, described fully in [14], a (spherical) particle overlapping with a neighbor or boundary wall feels a reaction force in the normal and tangential directions, as well as a host of particular damping effects that can optionally impose kintetic, static, rolling, and/or twisting friction. Plausible values for these various material parameters are obtained through comparison with laboratory experiments.

Figure 2: An artistic representation of a kinetic impactor mission to a hazardous object. This approach is one of those being studied by the NEOShield consortium for its efficacy in mitigating an NEO threat. As the impactor collides with the target, it is observed by a companion spacecraft in orbit around the object.

(Credit: ESA)

The numerical approach has been validated in terrestrial contexts; e.g., [14] demonstrated that `PKDGRAV`, using the soft-sphere collisional routine, correctly reproduces experiments of granular flow through cylindrical hoppers, specifically the flow rate as a function of aperture size, and found that the material properties of the grains affect the flow rate as well. Also successfully simulated were laboratory impact experiments into: (a) sintered glass beads [15], taking into account interparticle cohesion; (b) regolith in support of asteroid sampling mechanism design [16].

To carry out the initial phase of an impact, we generally use smoothed particle hydrodynamics (SPH) coding software [17] to handle the potion of the evolution of the impact that involves supersonic motion. The computed positions and velocities of the simulated material are then ported into `PKDGRAV` (Fig. 1), taking advantage of its gravity tree solver to find neighbors and to resolve gravitational forces, and its soft-sphere collisional routine to resolve contact forces. The momentum imparted to the model NEO is analyzed, and, the early evolution of the impact ejecta is computed, accounting for the mutual gravitational attraction between ejecta particles as well as the gravitational attraction due to the presence of the target. This is performed in order to determine ejecta fate, i.e, whether it re-collides, escapes, or enters into orbit around the target body. This has inherent scientific interest, as it pertains to the constitutive properties of these small bodies. In addition, this information is particularly important for the mission profile of an orbiting artificial satellite injected into the system in order to record the event (Fig. 2) in light of the potential observational and mechanical effects of lingering dust and debris. Results of simulations over a first set of impact conditions and material paramters will be discussed.

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