MOMENTUM TRANSFER IN IMPACT CRATERING OF A POROUS TARGET.

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Introduction: A variety of techniques have been proposed to deflect an asteroid that is on a collision course with the Earth. One method is to impact the asteroid with a heavy spacecraft, changing its orbit. Impacts of this type also happen naturally to the asteroids.

The European Space Agency and Johns Hopkins University's Applied Physics Laboratory are studying a mission, the Asteroid Impact and Deflection mission (AIDA), to test this technique of asteroid deflection. AIDA would intercept asteroid 65803 Didymos, a binary system with the larger body ~800 meters wide and the smaller body ~150 meters wide, in 2022, when Didymos makes its closest approach to Earth, at a distance of 11 million kilometers. The AIDA mission would have two spacecraft, the U.S Double Asteroid Redirection Test (DART), which would collide with the smaller body at ~6.25 km/sec, changing the rate at which the objects orbit around each other, and ESA's Asteroid Impact Monitor (AIM), which would measure the properties of the asteroids and observe the effects of the collision, particularly the momentum change.

The capability and technologies to deflect an asteroid's trajectory have never been demonstrated. Although the NASA Deep Impact mission delivered a kinetic impactor to comet 9P/Tempel 1, the impactor was so small (~370 kg impacting at ~10.7 km/sec delivering 1.96×10^{10} joules of kinetic energy), that it produced no detectable deflection of the large (~7.6 km×4.9 km) comet. Even if the amount and direction of the desired deflection is precisely known, the mass and speed of an impactor that will produce that deflection is not known because the dynamics of hypervelocity impacts and the physical properties of asteroids are not well understood. AIDA would validate models of impact and collisional physics on a large scale body.

Asteroid Response to Cratering: The recoil of an asteroid in response to an impact cratering event has two components: 1) the direct transfer of momentum by the impacting projectile, and, 2) the recoil of the asteroid from the crater ejecta.

Conservation of linear momentum limits the fraction of the projectile's kinetic energy that can be directly transferred as kinetic energy to the target. If the projectile is absorbed by the target this fraction is:

$$\text{K.E. change of target} = [m/(m+M)] \times \text{K.E.projectile}$$

Where m is the mass of the projectile and M is the mass of the target. If m/M is small, as was the case for Deep Impact there is very little direct transfer.

The crater ejecta also gives rise to momentum transfer to the target since, in a cratering event, all of the ejecta is directed into the half-plane away from the asteroid surface. Hypervelocity impact cratering into a non-porous asteroid can produce a significant mass of high-speed ejecta, resulting in a significant increase in momentum of the asteroid. Modeling suggests that momentum added by the crater ejecta can exceed that from direct momentum transfer by a factor of ten or more [1]. The total momentum gain of the target can be characterized by the factor β:

$$\beta = (m_p v_p + p_e)/m_p v_p = M_t V_t/m_p v_p$$

where p_e is the momentum of the ejecta and m_p and v_p are the mass and velocity of the impactor, and M_t and V_t are the mass and gain in velocity of the target. The $m_p v_p$ term is the direct momentum transfer and the p_e term is the momentum provided by the crater ejecta.

For a porous target both the mass and speed of the crater ejecta are modeled to be substantially less than for a non-porous target, with $\beta < 2$ for porous materials and impact speeds <15 km/sec [1]. Many asteroids are believed to be highly porous because they have bulk densities that are significantly lower than the minerals out of which they are made. Asteroid 253 Mathilde, for example, has a bulk density of only 1.3 gm/cc [2], indicating that its interior contains large void spaces or that it consists of small fragments with substantial interparticle porosity. Meteorites, and likely their parent asteroids, have significant porosity, ranging from ~10% for unweathered ordinary chondrites [3] to ~35% for the carbonaceous chondrite Orgueil [4].

In our prior hypervelocity cratering experiments on a porous, pumice target we found a very low mass of ejecta [5], consistent with a low recoil momentum. Other experiments on ordinary and carbonaceous chondrite meteorites indicate it requires twice as much energy to produce a similar disruption of these meteorites as it requires for a non-porous basalt target [6], again suggesting a significant amount of energy goes into compaction rather than disruption or cratering.

Procedure: To quantitatively determine the momentum transfer in a hypervelocity cratering event in an extremely porous target we suspended pumice targets, having $\rho \sim 0.4$ to 0.6 gm/cc, in front of a large rectangular grid in the vacuum chamber of the NASA Ames Vertical Gun Range (AVGR), as shown in Figure 1. We then impacted two pumice targets with Al projectiles having speeds of ~4 km/sec, close to the mean collision speed in the main-belt and the impactor speed of the proposed AIDA mission. The recoil of each target was recorded on high-speed video, with a frame rate of 6900.891 frames/sec.

The first target, having a mass of 297 gm, was impacted by a 1/8th inch Al projectile (mass = 0.0459 gm) at a speed of 3.92 km/sec. The impact produced a crater, with an entry hole 17x19 mm across and a depth of 25 mm, and ~4 gm of ejecta that was clearly visible in the video. Frame by frame analysis of the video gave a momentum transfer to the target corresponds to β ~ 2.3, consistent with a mean ejecta speed ~50 m/sec.

The second target, having a mass of 232 gm was impacted by a 1/8th inch Al projectile (mass = 0.0457 gm) at a speed of 4.05 km/sec. The impact initially produced a crater, 28x22 mm across with a depth of 19 mm, but a crack developed and the bottom of the target then separated from the top portion, as shown in Figure 1. The two largest fragments were 112 and 107 gm. Because the target disrupted, we obtained only an upper limit, $\beta \geq 2$, from the analysis of the video.

Conclusions: Even in this extreme case of these very high porosity targets (ρ ~0.5 gm/cc), well below the lowest density reported for any asteroid, the momentum enhancement from the crater ejecta equals or exceeds the direct momentum transfer. This indicates that, even for the most porous asteroid targets, momentum transfer by the crater ejecta is likely to contribute significantly to any asteroid deflection. Similar measurements on porous meteorite targets, which have significantly higher densities than the pumice employed in these experiments, should provide insights into the expected response of their asteroid parent bodies to the impact cratering.

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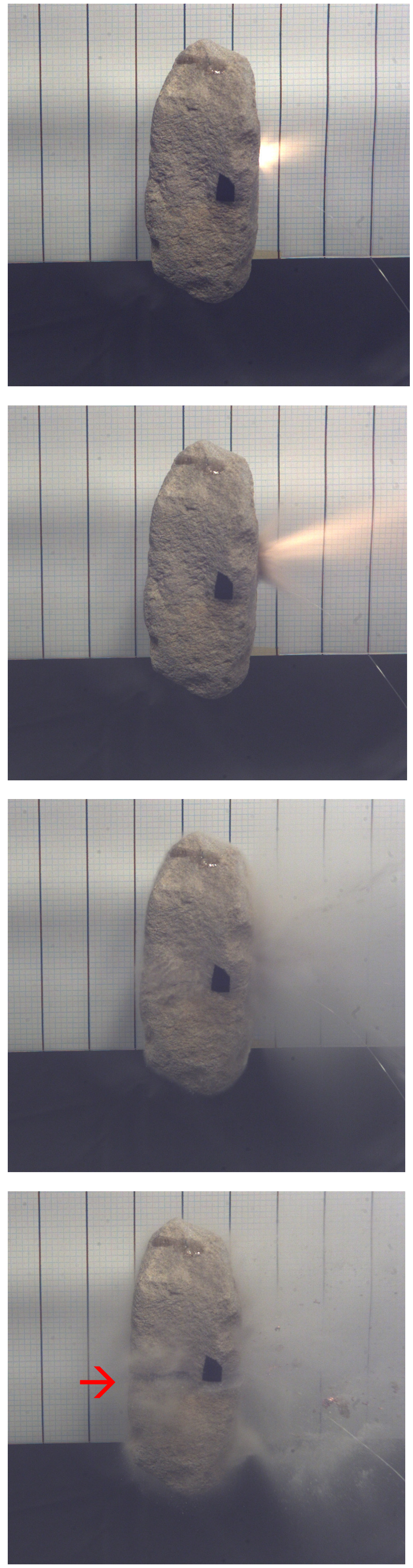

Figure 1: Four frames from the high speed video (6900.891 fps) of the 232 gm pumice target impacted by a 1/8th inch Al projectile. Frame 1878 (top) shows the instant of impact, frame 1879 (second) shows the crater ejecta, frame 1894 (third) shows the recoil of the target, and frame 1936 shows the beginning of a crack (arrow) where the top and bottom of the target separated from one another.