EPSC Abstracts
Vol. 11, EPSC2017-292, 2017
European Planetary Science Congress 2017

Momentum Enhancement from Hypervelocity Crater Ejecta: Implications for the AIDA Target

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Abstract

Porosities of asteroids range from 0 to >50%, with most >20%. Meteorites, which sample asteroids, have a similar range. Since porous targets react differently to hypervelocity cratering than non-porous targets, it is critical to measure the response of asteroid samples to impacts. We impacted 13 meteorite targets by 1/16" Al-spheres shot at 4.34 to 5.89 km/s at the NASA Ames Vertical Gun Range. Using high-speed video images we measured the recoil speed of each target and determined the momentum multiplication factor (β), the ratio between the recoil momentum of the target and the momentum of the impactor. For the meteorites β decreased with increasing porosity, with β = 3.37 for NWA 4502 (mean porosity 2.1%), 2.70 for NWA 869 (mean porosity 6.4%), and 1.49 for Saratov (porosity 15.6%), consistent with hydrocode modeling, but the highly porous pumice gave a higher value of ~2.2. These β values are larger than results from hydrocode modeling for 5 km/s impacts into porous rock targets. Although little is known about the Asteroid Impact and Deflection Assessment (AIDA) target, the ~160 m moon of asteroid Didymos, the model porosity of Didymos itself is ~40%. If the Didymos moon has similar properties, our β values for Saratov and terrestrial pumice likely provide the best starting point for modeling behavior of the target of the AIDA mission.

1. Introduction

The physical properties of meteorites are quite different from those of compact terrestrial rocks, whose properties are frequently used in modeling the behavior of the asteroids that are the parent bodies of the meteorites. For example, hypervelocity impact experiments by Flynn and Durda [1] demonstrated that it requires more than twice as much impactor kinetic energy per unit target mass to produce the equivalent disruption of an ordinary chondrite meteorite as it does for a terrestrial basalt target.

1.1 Momentum enhancement by ejecta

The momentum change 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 in response to the crater ejecta, which is directed in the half-plane away from the surface of the asteroid. The total momentum gain of the target is characterized by the momentum multiplication factor, β, which is the ratio of the change in momentum of the target to the pree-impact momentum of the impactor. If the only contribution to the momentum gain is the direct transfer by capture of the projectile, then β is equal to 1. Any momentum transfer due to the crater ejecta increases the β value, where β - 1 is the increase in momentum due to the ejecta.

1.2 Importance of β for kinetic deflection

Kinetic impactor deflection of an asteroid on a collision course with Earth was described in a 2007 NASA Report to United States Congress as "the most mature approach and could be used in some deflection/mitigation scenarios, especially for NEOs that consist of a single small, solid body." However, the value of β is the major uncertainty associated with the use of kinetic impact to deflect hazardous asteroids, especially for porous target asteroids.

Hydrocode modeling indicates the momentum added by the crater ejecta can exceed that from direct momentum transfer by a factor of ten or more for hypervelocity impacts into non-porous rock targets, but there is a significant decrease in β with increasing porosity or decreasing impactor speed. Modeling by Jutzi and Michel, in support of the proposed Asteroid Impact and Deflection Assessment (AIDA) mission, indicates both porosity and strength can have a large effect on β, with $\beta < 2$ for impactor speeds $\leqslant$15 km/s into moderately porous targets [2].

1.3 The AIDA target

The AIDA target is the 160 m diameter satellite orbiting asteroid Didymos. The mass and shape of the Didymos, indicate a bulk density of ~2.15 g/cm^3 and its reflection spectrum suggests Didymos is an S-type asteroid, the type sampled by ordinary chondrite meteorites. Using the mean grain density for ordinary chondrite meteorites, varying from 3.52 g/cm^3 for LL ordinary chondrites to 3.71g/cm^3 for H ordinary chondrites, we infer a model porosity for Didymos ranging from 39% to 42%. Very little is known about the composition or physical properties of the secondary, which is the AIDA target, but if the secondary is a fragment of Didymos, it likely has a similar composition and porosity.

2. Samples and Procedure

We conducted hypervelocity cratering experiments of 13 samples of three different chondritic meteorites spanning porosities from 2% to 16%, and 2 high porosity terrestrial pumice samples.

2.1 Samples

We conducted 5 cratering impacts of the minimally weathered (W1) and minimally shocked (S2) dry CV3 carbonaceous chondrite Northwest Africa (NWA) 4502, two samples of which had porosities of 1.2 and 3.0% with a mean porosity of 2.1%**.** NWA 4502 is an unusual CV3 carbonaceous chondrite in that it is at the lower end of the porosity range for this type of meteorite. We conducted 7 cratering impacts of the minimally weathered (W1) and moderately shocked (S3) Northwest Africa (NWA) 869 L3-6 ordinary chondrite, which had porosities ranging from 2.7% to 10.2% with a mean porosity of 6.4%. The porosity of NWA 869 is within the typical range for ordinary chondrites. We conducted one cratering impact of the L4 ordinary chondrite Saratov, a fall with minimal weathering and minimal shock (S2), with porosities of two similar samples of 15.2 and 16.1% and a mean porosity of 15.6%, making it one of the most porous ordinary chondrite meteorites. To further extend the range, we impacted two terrestrial pumice targets with ~70% porosity.

2.2 Procedure

We hung each meteorite target directly in front of a grid in the sample chamber of the NASA Ames Vertical Gun Range (AVGR). Each meteorite target was impacted by a 1/16" Al sphere shot at a speed ranging from 4.34 to 5.89 km/s. This speed range is comparable to the mean collision speed between asteroids in the main belt and similar to the impactor speed proposed for AIDA. We acquired image sequences using five high-speed video cameras, measured the recoil speed from these images, and determined β for each impact.

3. Results and Conclusions

Four of the five cratering impacts into NWA 4502 targets produced β values in the narrow range from 2.88 to 3.97, with a mean β of 3.37 ± 0.5. One shot produced a remarkably different value of β equal to 11.72, likely an impact into hydrous terrestrial weathering material rather than anhydrous meteorite material. All seven of the cratering impacts into NWA 869 targets produced β values in the narrow range from 1.82 to 3.81, with a mean β of 2.71 ± 0.6. The single Saratov cratering event produced a β value of 1.49, and the two pumice impacts produced a β of ~2.2. Our Saratov β = 1.49 and pumice β = 2.2, bracketing the porosity range expected for the moon of Didymos, are larger than results from hydrocode modeling for impacts into weak rocks, which gave β values <1.2 for 10 km/s cratering events over this porosity range [3], and serve as a starting point for modeling the AIDA kinetic impact.

Acknowledgements

This work was supported by NASA Solar System Workings grant # NNX15AM22G. We thank the NASA AVGR crew, whose efforts were critical to the success of this project.

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