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Hypervelocity Cratering Recoil of Meteorites and Analogs

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Abstract

We measured the momentum transferred in ~5 km/s cratering of hydrous and anhydrous meteorite and meteorite analog targets spanning a wide range of porosity. In each case the momentum from crater ejecta exceeded that from projectile capture, and the values modeled for impact into moderately strong rocks. The crater ejecta in hydrous impacts produced significantly more recoil momentum than we found for anhydrous targets of similar porosity.

1. Introduction

Porosities of asteroids range from 0 to >50%, with most >20% [1], and some asteroids exhibit a 0.7 micron water feature in their spectra [2]. Both porosity and hydration are expected to influence the momentum transferred in collisions. We conducted a series of hypervelocity cratering impacts on meteorites, which are fragments of asteroids, and on meteorite analogs for asteroid types too rare among the meteorites to be available for destructive analyses. We measured post-impact momenta, characterized by β, the ratio of the total linear momentum acquired by the target to the momentum of the impactor.

1.1 Samples

We determined β for anhydrous meteorites spanning a wide range of porosities, including 5 samples of the CV3 carbonaceous chondrite Northwest Africa (NWA) 4502, 7 samples of the ordinary chondrite NWA 869, and 4 samples of the ordinary chondrite Saratov, as well as 2 samples of high porosity terrestrial pumice. We also measured hydrous meteorite analog targets, including 3 samples of terrestrial serpentine and 4 samples of terrestrial montmorillonite, the two clay minerals that dominate the hydrous CI carbonaceous chondrite meteorites, as well as 4 samples of hydrous meteorite analog material. We measured porosities and compressive strengths of representative samples of most of the types of meteorites or analogs in this study.

1.1 Experimental Procedure

Each target was hung at the end of a light nylon string about 2 m in length and suspended from the ceiling in the target chamber of the two-stage light gas gun at the NASA Ames Vertical Gun Range (AVGR), which is described by Karcz et al. [3]. Spherical Al-projectiles of 1/16" or 1/8" diameter were fired at each target at speeds ranging from about 4.0 km/s to about 5.9 km/s. To determine β, the recoil speed of each target was measured from high speed video sequences (initially 6,900 frames/s and 71,000 frames/s since 2016). To minimize the effect of gas emitted by the gun, a mylar disk was located downstream from the sabot stripper, and a paper disk was placed over the exit port of the gun chamber. Both are easily penetrated by the projectile, but diffuse any gas emitted by the gun. "Blank" shots using the normal powder load for a 5 km/s shot with a 1/16" Al projectile were fired with one of the smallest targets each year. For each blank shot the high-speed video sequence showed no measurable target recoil, demonstrating that gas from the gun did not transfer significant momentum to the targets.

2. Results

NWA 4502 is a minimally weathered (W1) and minimally shocked (S2), oxidized CV3 carbonaceous chondrite. Porosities of two whole stones are 3.0% and 1.2% (mean porosity 2.1% ± 0.9%), which is much lower than the mean porosity of 17.7% ± 1.0% for oxidized CV3 falls. Compressive strengths of four samples ranged from 18.9 to 58.8 MPa (mean of 32.9 ± 17.8 MPa), comparable to the range reported for the CV3 meteorite Allende [4]. Five of the seven cratering impacts into NWA 4502 targets produced β values in the narrow range from 3.02 to 3.93, with a mean β of 3.55 ± 0.38. Two shots produced remarkably different values of β, 8.95 and 11.72, suggesting the impactor in these shots struck a different material, likely the hydrous weathering veins present in our samples. This prompted an extension of our investigation to hydrous targets.

NWA 869 has a weathering grade W1 (minimal weathering), and a shock stage S3, indicating it was only weakly shocked (15 to 20 GPa). Porosities of six fragments ranged from 2.7% to 10.2%, with a mean of 6.4% ± 2.8%, consistent with L-chondrite falls. Unconfined compressive strengths of the six samples of NWA 869 ranged from 52 to 114 MPa, with a mean of 87.4 ± 25.6 MPa, comparable to the range reported for L-type ordinary chondrites [4]. All seven impacts produced β values in the narrow range from 1.94 to 3.74, with a mean of 2.69 ± 0.42.

Saratov is an L4 ordinary chondrite fall that shows minimal weathering and minimal shock (S2). Two Saratov samples gave a mean porosity of 15.6% ± 0.6%, much of this in the form of interstitial voids rather than the cracks seen in many meteorites. All four of the Saratov cratering impacts produced β values in the range from 1.49 to 2.84, a mean β of 2.1 ± 0.6. Saratov has an unusually high porosity among ordinary chondrites, almost double the mean of 8.0 ± 0.3% for L-chondrites falls [4]. To extend our measurements to even higher porosity we impacted two samples of terrestrial pumice, with porosity of ~80%, which produced β values of 2.3 and 2.0, giving a mean β of 2.15 ± 0.21

Samples of hydrous meteorites large enough for hypervelocity cratering, rather than disruption, could not be obtained, so we used analogs to investigate the effect of hydration on recoil. Targets of serpentine (mean porosity 17.9% ± 1.3%) and montmorillonite (mean porosity 51.5% ± 0.2), the two clay minerals that dominate the mineralogy of CI meteorites, gave β of 4.7 ± 0.4 and 2.8 ± 0.5 respectively. Laboratory hydrated samples were prepared from NWA 4502 using a procedure simulating, at a shorter time scale, the hydration process on asteroids, which was shown to produce CI-like material [5]. These targets, with a porosity of ~26%, give a mean β of 2.99 ± 0.84.

3. Summary and Conclusions

The mean β values for the anhydrous targets and for the hydrous targets (Figure 1) show two clear trends. First, β decreases with increasing porosity, consistent with results of hydrocode modeling. However, the β values on porous targets are significantly larger than predicted by much of the hydrocode modeling of strong rocks. Second, the β for each of the hydrous targets is significantly greater than that for an anhydrous target of similar porosity, suggesting hydration, common for carbonaceous asteroids, substantially enhances momentum transfer, likely by jetting of water vapor. For each type of stone target we measured, over the full range of the porosity investigated, the ratio of the momentum transferred by the crater ejecta to the momentum of the projectile (β − 1) is >1. Thus, momentum enhancement by crater ejecta should be considered in design of kinetic impact deflection missions and modeling of the alteration of asteroid or comet orbits by collisions.

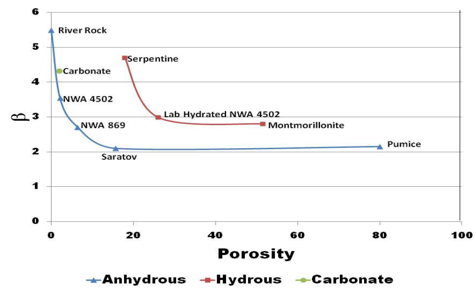

Figure 1: Mean porosity vs. β for anhydrous and hydrous meteorite and meteorite analog targets.

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