Proceedings of the 2019 Hypervelocity Impact Symposium
HVIS2019
April 14-19, 2019, Destin, FL, USA
HVIS2019-028

Extended Abstract+

Momentum transfer in hypervelocity cratering of meteorites and meteorite analogs: Implications for asteroid deflection

George J. Flynn[a*], Daniel D. Durda[b], Mason J. Molesky[c], Brian A. May[c], Spenser N. Congram[c], Colleen L. Loftus[c], Jacob R. Reagan[c], Melissa M. Strait[c], Robert J. Macke[d]

[a]*SUNY-Plattsburgh, 101 Broad St., Plattsburgh, NY 12901 USA*
[b]*Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302 USA,*
[c]*Alma College, Alma, MI 48801 USA*
[d]*Vatican Observatory, V-00120 Vatican City*

Abstract

Asteroid porosity ranges from 0 to >50%, with most >20%, and some asteroids exhibit a water feature in their reflection spectra. Porosity and hydration are expected to influence the momentum transferred in hypervelocity collisions. We conducted a series of measurements of the post-impact momentum, characterized by a factor β, the ratio of the total linear momentum acquired by the target to the momentum of the impactor. We measured β for anhydrous meteorites, samples of their asteroidal parent bodies, spanning a wide range of porosities: 7 samples of the CV3 carbonaceous chondrite Northwest Africa (NWA) 4502 (2.1% porosity), 7 samples of the ordinary chondrite NWA 869 (6.4% porosity), and 4 samples of the ordinary chondrite Saratov (15.6% porosity), as well as 2 samples of terrestrial pumice (80% porosity). We also measured hydrous meteorite analog targets, including 2 samples of terrestrial serpentine (17.9% porosity) and 4 samples of terrestrial montmorillonite (51.5% porosity), the two clay minerals that dominate the composition of the hydrous CI carbonaceous chondrite meteorites, as well as 4 samples of hydrous meteorite analog material prepared by powdering and hydrating an anhydrous carbonaceous chondrite. We found that for both anhydrous and hydrous samples β decreased with increasing porosity, consistent with hydrocode modeling. The β for each target type was >2 demonstrating that crater ejecta makes a significant contribution to recoil in hypervelocity collisions.. The β values we measured for the anhydrous samples are larger, with β = 3.55 for NWA 4502, 2.69 for NWA 869, 2.10 for Saratov, and 2.15 for pumice, than results from hydrocode modeling for 10 km/s impacts into relatively strong, porous rock targets. The momentum enhancement by ejecta (β - 1) for the moderate porosity (17.9%) hydrous serpentine targets (β = 4.70), the highly porous (51.55% porosity) hydrous montmorillonite targets (β = 2.79), and the intermediate porosity (~26%) CI-analogs (β = 2.99) are much larger than β value for anhydrous targets of similar porosity, indicating jetting of water vapor could significantly affect deflection of hydrous asteroids and comets in natural or human-induced collisions.

Keywords: hypervelocity cratering; meteorites; asteroids; kinetic impact deflection, hydrous targets.

1. Introduction

The response of asteroids or comets to hypervelocity impact influences the morphology and size of craters, the orbital change resulting from collisions, fragmentation in catastrophic collisions, and the size-frequency distribution and the speed distribution of dust produced by the impact. The physical properties of asteroids and comets are important in understanding the change to their orbits from natural or human-induced collisions. The extent of this alteration is important for asteroid or comet orbital evolution modeling and for attempts to deflect an asteroid or comet on a collision course with Earth using a kinetic impactor or a

+ Full paper can found at https://www.sciencedirect.com/journal/international-journal-of-impact-engineering/special-issue/10MTGP5W4VJ

* Corresponding author. Tel.: +1-518-564-3163.
E-mail address: flynngj@plattsburgh.edu.

surface/subsurface nuclear explosion. The momentum transferred to the target in a hypervelocity impact is characterized by a factor β, the ratio of the total linear momentum acquired by the target to the linear momentum of the impactor, given by:

$$\beta = (m_p v_p + p_e)/m_p v_p = M_t V_t / m_p v_p \qquad \text{(Equation 1)}$$

where m_p is the mass of the projectile, v_p is the speed of the projectile, p_e is the magnitude of the momentum of the crater ejecta opposite the recoil direction, M_t is the mass of the target, and V_t is the change in speed of the target due to the impact. Two major factors contribute to β: the momentum of the impactor and the recoil from crater ejecta produced in the impact.

Porosities inferred for nearly two dozen asteroids range from nearly zero to >50%, with most >20% and with a mean of ~30% [1]. Asteroids exhibit a diversity of mineralogies. Reflection spectra show the inner half of the main-belt is dominated by S-type asteroids, believed to be similar to ordinary chondrite meteorites, a link firmly established when samples from S-type asteroid Itokawa were shown to have mineralogy and mineral chemistry identical to those of thermally metamorphosed LL ordinary chondrites [2]. The outer half of the main belt is dominated by darker asteroids, mainly classified as C-type, which are believed to be similar in composition to carbonaceous chondrite meteorites. Reflectance spectra of some show a 0.7-µm feature, indicating the presence of hydrous minerals [3]. These dark hydrous asteroids are similar to the hydrous CI or CM carbonaceous chondrite meteorites, while the dark, anhydrous asteroids are likely similar to the anhydrous carbonaceous chondrites, mainly CV or CO meteorites. The recovery of meteorites spanning the range of mineralogies seen among the asteroids demonstrates that members of each type occur in the Near Earth Object (NEO) population. Mineralogy, porosity and water content each effect the response to hypervelocity impact. The average velocity of crater ejecta decreases with decreasing material strength and with increasing porosity [4], and the recoil of liquid water targets is more than 10 times that of dry rocks [5].

At the 2017 Hypervelocity Impact Symposium, we reported hypervelocity recoil results from samples of three anhydrous meteorites spanning a range of porosities, including five cratering impacts of the low porosity CV3 carbonaceous chondrite Northwest Africa (NWA) 4502, seven cratering impacts of the intermediate porosity NWA 869 L3-6 ordinary chondrite, and one cratering impact of the high porosity L4 ordinary chondrite Saratov [6]. For each target type the β values were tightly clustered except for one cratering impact into NWA 4502, which gave a β value more than three times the other NWA 4502 impacts. We suggested that impactor struck a vein of hydrous weathering product. We have extended that work to include more samples of NWA 4502 and Saratov and hydrous targets of montmorillonite, serpentine, and laboratory hydrated CI-analog material.

1.1. Samples and Experimental Procedures

We have measured the momentum transfer in hypervelocity cratering for 18 anhydrous meteorite targets spanning a range of porosities from 2.1% to 15.6%, and 2 samples of terrestrial pumice (80% porosity) to extend anhydrous target measurements to higher porosity than is sampled by meteorites. We also measured momentum transfer for hydrous meteorite analogs, including 2 samples of terrestrial serpentine (18% porosity) and 4 samples of terrestrial montmorillonite (55% porosity), the two clay minerals that dominate in the hydrous CI meteorites [7]. These CI carbonaceous chondrites are rare and generally unavailable in large enough pieces for cratering measurements, but they are represented in the NEO population. For example Bennu, the target of NASA's OSIRIS-REx sample return, is a primitive, hydrous, carbon-rich asteroid with bulk density of 1.26 g/cm^3 and porosity of 40% ± 10% [8]. This suggests similarity to the CI meteorite Orgueil, which has a bulk density of 1.5 g/cm^3 [9]. To investigate the cratering recoil of CI-like targets we prepared hydrous meteorite analog targets. Fragments of NWA 4502 were crushed to a fine powder and laboratory hydrated in slightly alkaline water at high temperature in a pressure bomb for months, using a procedure intended to mimic, on a shorter time scale, the hydration process that occurs on asteroid parent bodies [10].

The measurement procedures for the grain and bulk densities, unconfined compressive strengths and recoil speeds are described in Flynn et al. [6]. Each target was suspended on a light nylon string about 2 m in length in the target chamber of the two-stage light gas gun at the NASA Ames Vertical Gun Range (AVGR). The AVGR Chamber was pumped to ~0.5 Torr to minimize atmospheric interference with the projectiles. The gun launched a nylon sabot containing a 1/16th or 1/8th inch diameter Al-sphere. After the sabot was stripped from the projectile the speed was measured using a laser-interrupt system, and the projectile was imaged to verify its structural integrity. Projectile speeds ranged from ~4 km/s to ~5.9 km/s, comparable to the mean collision speed in the main-belt [11]. 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. We confirmed that there was no detectable target recoil when the gun was fired with a normal powder load but no projectile. High-speed video cameras were located in the viewing ports of the AVGR chamber, and we determined β by measuring the recoil speed (V_t) of the target relative to the 1x1inch grid pattern and combining this with the target mass, impactor mass and speed using Equation 1. In four cases the targets split into roughly equal fragments, with only a small mass of additional material. In these cases we determined the speed of each fragment and β was determined from the sum of the linear momentum transferred to each fragment.

2. Results

The typical mass of the crater ejecta is hundreds of times the mass of the impactor, thus even a relatively low mean ejecta speed produces a significant recoil momentum.

2.1 Anhydrous Targets

NWA 4502 is a minimally weathered (W1) and minimally shocked (S2), oxidized CV3 carbonaceous chondrite. Porosities of two of NWA 4502 whole stones are 3.0% and 1.2% (mean porosity 2.1% ± 0.9%), which is much lower than typical, since Macke [12] reported a mean porosity of 17.7% for oxidized CV3 falls. This low porosity is consistent with the observations that the matrix of NWA 4502 is unusual, being "rather compact" [13], since most meteorite porosity is within the matrix as cracks or as voids between the grains. The unconfined compressive strengths of four samples of NWA 4502 ranged from 18.9 to 58.8 MPa, with a mean of 32.9 ± 17.8 MPa, comparable to the unconfined compressive strength of the CV3 meteorite Allende [14]. 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, consistent with the relatively narrow range of β values for other types of targets. They produced ejecta masses, the difference between the initial target mass and the masses of the largest fragments, ranging from 3.0 g to 18.0 g, with a mean ejecta mass of 10.3 g. In each case the ejecta mass was more than 500 times the mass of the impactor. Two NWA 4502 shots produced remarkably different values of β, 8.95 and 11.72, with consistent values from both camera angles. This suggests these impactors struck a different material than the other five NWA 4502 cratering impacts. Although NWA 4502 was collected in a dry desert, terrestrial weathering can still occur relatively rapidly [15], so we suspected impact into hydrous weathering veins, which are prominent on the surfaces of our NWA 4502 stones, gave rise to these higher β values [6]

NWA 869 has a weathering grade W1, indicating that there are only small oxide rims around metal and troilite and small oxide veins, and a shock stage S3, indicating it was only weakly shocked (15 to 20 GPa). We measured the porosities of six fragments of NWA 869. The mean grain density of these six samples of NWA 869, 3.58 ± 0.08 g/cm^3, the same as the mean value of 3.58 ± 0.01 g/cm^3 reported by Macke [12] for L-chondrite falls, consistent with minimal effects from terrestrial weathering, which lowers the grain density. The mean bulk density of these six samples, 3.36 ± 0.04 g/cm^3, consistent with the mean value of 3.30 ± 0.01 g/cm^3 reported by Macke [12] for L-chondrite falls. The porosity values ranged from 2.7% to 10.2%, with a mean of 6.4% ± 2.8%, slightly lower than typical for L-chondrite falls (8.0% ± 0.3% [12]). The unconfined compressive strengths of the six samples of NWA 869 ranged from 52 to 114 MPa, with a mean value of 87.4 ± 25.6 MPa, comparable to the range reported for L-type ordinary chondrites [16]. All seven of the cratering impacts into NWA 869 targets produced β values in the narrow range from 1.94 to 3.74, with a mean β of 2.69 ± 0.42. They produced ejecta masses ranging from <0.5 g to 5.0 g, with a mean ejecta mass of 2.3 g, much lower than the ejecta masses produced in the NWA 4502 cratering impacts.

Saratov is an L4 ordinary chondrite, showing minimal weathering and shock (S2). We measured porosities of two Saratov samples of 15.2% and 16.1%, giving a mean porosity of 15.6% ± 0.6%, much in the form of interstitial voids rather than cracks. Saratov has unusually high porosity among ordinary chondrites, almost double the mean of 8.0% ± 0.3% for L-chondrite falls [12]. All four of the Saratov cratering impacts produced β values in the range from 1.49 to 2.84, a mean β of 2.10 ± 0.60.

To extend our anhydrous targets to higher porosity we impacted samples of highly vesicular, rough-textured terrestrial pumice. We cut ten rectangular blocks, averaging about 1 g with volumes ~2 cm^3, from an unshot pumice sample. These had densities ranging from 0.45 to 0.62 gm/cm^3, with a mean density of 0.538 ± 0.059 g/cm^3. Taking literature values of 2.4 to 2.8 g/cm^3 as representative of non-porous samples, we estimate the porosity of these pumice targets to be in the range of 77 to 82%. The two pumice impacts produced β values of 2.3 and 2.0, giving a mean β of 2.15 ± 0.21.

2.2 Hydrous Targets

To investigate the effect of hydrous minerals on cratering recoil we used targets of serpentine and montmorillonite, the two clay minerals that dominate the structure of CI meteorites [7]. We measured the porosities of two serpentine samples as 17.0 and 18.8%, giving a mean porosity of 17.9% ± 1.3%, and two samples of montmorillonite as 51.60% and 51.35%, giving a mean porosity of 51.5% ± 0.2%. A 61.96 g serpentine sample was immersed in water for two days before the shot in an attempt to add liquid water to the target. Its mass increased to 64.89 g, adding almost 3 g of water. However, we could not determine how much water was lost during the more than half-hour interval while the AVGR chamber was pumped to ~0.5 torr before the shot. These two serpentine impacts gave β values of 4.40 and 4.93, with a mean β of 4.7 ± 0.4. The values are quite similar for the two samples, indicating that the immersion in water did not change the β value, possibly because of water evaporation during pump down of the AVGR chamber. Four montmorillonite impacts gave β values in the range from 2.10 to 3.34, with a mean β of 2.8 ± 0.5. Both of these β values are significantly higher than we measured for anhydrous targets of similar porosities.

Laboratory Hydrated NWA 4502 was prepared by crushing the CV3 NWA 4502 using a procedure shown by Jones and Brearly [10] to produce CI-like material. We confirmed the production of clays in our processing by infrared spectroscopy, but we cannot ensure complete alteration of anhydrous silicates to clays. The mean density of the resulting samples was ~1.8 g/cm^3. If the targets were fully hydrous then, using the mean grain density of the CI meteorites (2.42 g/cm^3 [12]), the porosity would be ~26%. Any remaining crystalline silicates would increase the mean grain density, thus giving even higher porosity. We performed four cratering impacts of these CI-like targets. These very weak targets could not be hung directly from the ceiling of the chamber, since they were so weak they would come apart under their own weight if the support line were attached to the top. So, we suspended each of these laboratory hydrated CI stimulant targets in a hair net sling of negligible mass compared to the target. The sling supported the bottom of the target, but it did not interfere with the incoming projectile or with the recoil speed of the target. This provided the necessary support without interfering with the projectile or recoil. The CI-analog targets were impacted at ~5 km/s. These four targets gave β values of 3.58, 3.83, 2.36, and 2.17, giving a mean β of 2.99 ± 0.84.

3. Discussion and Conclusions

Figure 1 shows the mean β for each of our stone target types as well as the value for low porosity river rock. Two trends are clearly evident. First, β decreases with increasing porosity, consistent with results of hydrocode modeling [17]. Second, the recoil enhancement due to crater ejecta for each of the hydrous targets studied is significantly greater than the value for an anhydrous target of similar density. These results suggest hydration substantially enhances momentum transfer, likely by jetting of water vaporized in the hypervelocity cratering event. The enhancement of β for hydrous targets has important implications for orbital evolution from natural collisions and momentum requirements for kineic or nuclear deflection of hydrous asteroids and icy comets. The β values we measured on anhydrous porous targets are significantly larger than predicted by hydrocode modeling of moderately strong porous rocks, since SPH modeling for 10 km/s cratering impacts into rocks (100 MPa strength) gave β <1.2 over this porosity range [17]. Our values for porous hydrous targets are even higher, but effects of water vaporization have not been modeled. For each stone target, over the full range of 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 ejecta must be considered in design of kinetic impact deflection missions and modeling of the alteration of orbits by collisions.

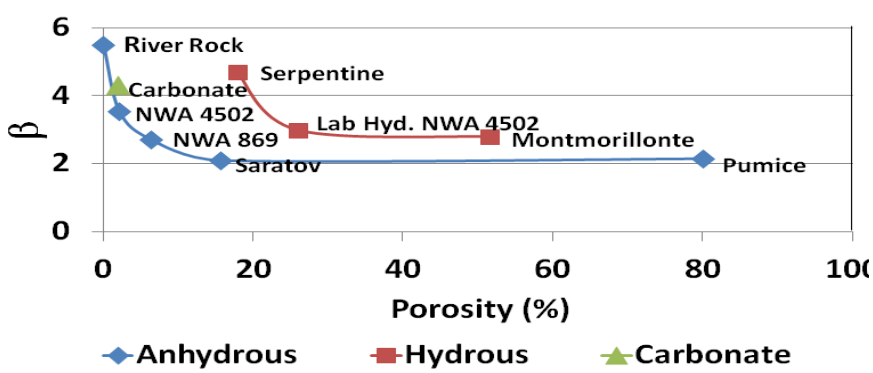

Fig. 1. Mean porosity vs. β for three types of anhydrous meteorite targets, NWA 4502, NWA 869 and Saratov, as well as terrestrial pumice and the river rock from Housen and Holsapple [18], as well as three hydrous CI-analog materials, serpentine, laboratory hydrated NWA 4502, and montmorillonite. Lines show the trend in β for anhydrous and hydrous targets.

References

[1] Britt, D.T., D. Yeomans, K. Housen, G. Consolmagno, 2002. Asteroid density, porosity, and structure, in Asteroids III, U. of Arizona Press, 485-500.
[2] Nakamura, T. and 21 co-authors , 2011, Itokawa Dust Particles, Science, 333, 1113-1116.
[3] Campins, H. and 5 co-authors, 2018. Compositional Diversity Among Primitive Asteroids, in Primitive Meteorites and Asteroids, Elsevier, 345-369.
[4] Michikami, T. and 3 co-authors, 2007. Ejecta velocity distribution for impact cratering experiments, Planetary and Space Science, 55, 70-88.
[5] Holsapple, K.A., K.R. Housen, 2012. Momentum transfer in asteroid impacts. I. Theory and scaling, Icarus, 221, 875-887..
[6] Flynn, G. J. and 7 co-authors, 2017, Hypervelocity impact cratering of chondritic meteorites, Procedia Engineering, 204:146-153.
[7] Bass, M.N., 1971. Montmorillonite and serpentine in Orgueil meteorite, Geochim Cosmochim. Acta, 35, 139-147.
[8] Chesley, S. R. and 15 co-authors, 2014. Orbit and bulk density of the OSIRIS-REx target Asteroid (101955) Bennu, Icarus, 235, 5-22.
[9] Britt, D.T. and G.J. Consolmagno, 2003. Stony meteorite porosities and densities, Meteorit. Planet. Sci., 38, 1161-1180.
[10] Jones, C.L., A. Brearley, 2006. Experimental aqueous alteration of the Allende meteorite, Geochim.. Cosmochim. Acta, 70, 1040-1058.

[11] Bottke, W.F., M. C. Nolan, R.Greenberg, and R.A. Kolvoord, 1994. Velocity distributions among colliding asteroids, Icarus, 107, 255–268.
[12] Macke R.J., 2010. Survey of meteorite physical properties: Density, porosity and magnetic susceptibility. Ph.D. dissertation. University of Central Florida.
[13] Sapah, M.S., A.N. Krot, Y. Amelin, 2013. Mineralogy and Petrography of Refractory Inclusions in NWA 4502, Lunar Planet. Sci. Conf. XLIV, Abs. #1036.
[14] Cotto-Figueroa, D. and 8 co-authors, 2016. Scale-dependent measurements of meteorite strength, Icarus, 277, 73-77.
[15] Al-Kathiri, A., B.A. Hofmann , A.J.T. Jull , E. Gnos, 2015. The Weathering of meteorites from Oman:, Meteoritics & Planet. Sci., 40, 1215-1239.
[16] Flynn, G.J., G.J. Consolmagno, P. Brown, R.J. Macke, 2018. Physical properties of the stone meteorites, Chemie der Erde, 78, 269-298.
[17] Bruck Syal, M., J.M. Owen, P.L. Miller, 2016. Deflection by kinetic impact: Sensitivity to asteroid properties, Icarus, 269, 50-61.
[18] Housen, K. R. and K. A. Holsapple , 2012. Deflecting Asteroids by Impacts: What is Beta?, Lunar and Planet. Sci. Conf.XLIII, Abst. #2539).