HYPERVELOCITY IMPACT CRATERING AND DISRUPTION OF THE CV3 CARBONACEOUS CHONDRITE NORTHWEST AFRICA 4502 AND THE SARATOV L4 ORDINARY CHONDRITE.

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Introduction: Kinetic impact has been suggested as an appropriate technique to deflect potentially hazardous asteroids from Earth impacting orbital paths. However, Syal et al. [1] have noted that "the efficacy of momentum delivery to asteroids by hypervelocity impact is sensitive to both the impact conditions (particularly velocity) and the specific characteristics of the target asteroid," making it critical to understand asteroid response to hypervelocity impacts.

Although porosities have only been inferred for a few dozen asteroids, most porosities range from 20% to >50%, with a mean porosity of ~30% [2]. Meteorites, which sample the asteroids, have a similar range of porosities, from nearly 0 to >40%. Porous targets react differently to impact cratering and disruption than non-porous targets. The physical properties of the meteorites vary from one to another type of meteorite, so we have begun a series of hypervelocity impact cratering and disruption experiments, each focusing on a specific meteorite. Our initial focus was on Northwest Africa (NWA) 869 [3], an L3-6 ordinary chondrite with shock state S3 and weathering state W1. We have extended those measurements to the CV3 carbonaceous chondrite Northwest Africa (NWA) 4502, which is described in the Meteoritical Bulletin Database as having shock state S2 and weathering state W1. However, we note that the samples we impacted were crosscut by cracks that appeared to be filled by weathering products. We also cratered one sample of the L4 ordinary chondrite Saratov, selected because other Saratov samples have relatively high porosity, 11.3 to 14.5% [4].

Momentum Transfer by Crater Ejecta: The momentum change of an asteroid in response to an impact cratering event has two components: 1) direct transfer of momentum by the impacting projectile, and 2) recoil of the asteroid in response to the crater ejecta. Although the ejecta direction is affected by the local topography, it is generally directed opposite the direction of the impactor, resulting in a momentum transfer that is in approximately the same direction as the direct momentum transferred by the projectile. Hypervelocity impact cratering into an asteroid can produce a significant mass of low speed ejecta, compared to the mass of the impactor. Thus, even low speed crater ejecta can produce a significant change in asteroid momentum.

The total momentum gain of the target can be characterized by the momentum multiplication 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, 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. Thus, if the only contribution to the momentum gain of the target is the direct momentum transfer due to projectile capture β will equal 1. Any additional momentum transfer from the crater ejecta increases the β value.

Modeling suggests the momentum added by crater ejecta can exceed that from direct momentum transfer by a factor of ten or more in non-porous targets [5]. In a hypervelocity impact experiment, Housen and Holsapple [6] measured a β = 5 for river rock impacted at ~5.5 km/s. They found progressively lower β values for impactors with lower speeds, and β is also modeled to decrease with increasing target porosity. Hydrocode modeling by Syal et al. [1] found β = 3.5 for impactors with a speed of 10 km/s, on targets with 1 kPa cohesive strength and porosities up to 50%, however β for 5 km/s impacts into 40% porous targets was lower.

To quantitatively determine the momentum transfer in a hypervelocity cratering event we suspended each meteorite target in front of a large rectangular grid in the vacuum chamber at the NASA Ames Vertical Gun Range. To minimize the effect on the target 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 hypervelocity Al projectile, but tend to diffuse the gas emitted by the gun. A "blank" shot was conducted in which the gun was fired, with the normal powder load for a 5 km/s shot with a 1/16" Al projectile, at a 135 g NWA 869 target, but no projectile was loaded. Analysis of the high-speed video showed no detectable recoil of the target [3].

The conditions and outcomes of seven hypervelocity impacts into NWA 4502 targets and one into a Saratov target are given in Table 1. Five of the NWA 4502 impacts and the one Saratov impact resulted in cratering events. The momentum enhancement factor, β, was derived from high speed video images of the target recoil recorded by cameras at the side and near the top of the AVGR chamber. Two NWA 4502 impacts, conducted under essentially identical conditions to the cratering impacts, resulted in target fragmentation.

Cratering Experiments: Four NWA 4502 cratering impacts gave consistent β values clustering between

Table 1: NWA 4502 and Saratov Impact Results

Shot #	Target	Target	Largest Frag.	Impactor	Impactor	Impactor	β
Cratering		Mass (g)	Mass (g)		Mass (g)	Speed (km/s)	
160804	NWA 4502	175	157	1/16"Al	0.0058	5.52	2.88
160805	NWA 4502	275	259	1/16" Al	0.0060	4.67	3.89
160807	NWA 4502	367	363	1/16" Al	0.0057	5.89	3.48
160808*	NWA 4502	363	352	1/16" Al	0.0060	4.81	8.95
160809**	NWA 4502	352	349	1/16" Al	0.0059	4.88	3.01
160812	Saratov	113	100	1/16" Al	0.0059	5.21	1.49
Disruptions							
160806***	NWA 4502	259	135	1/16" Al	0.0058	5.03	
160810	NWA 4502	453	187	1/16" Al	0.0059	5.69	

*Same target as used for Shot 160807 **Same target as used for Shot 160808 ***Same target as used for Shot 160805

2.88 and 3.89, with a mean β = 3.32, and an ejecta mass ~1,000 times the impactor mass. This value is slightly higher than the mean β = 2.71 previously reported for 7 hypervelocity cratering shots on NWA 869 [3]. NWA 4502 Shot 160808 gave β = 8.95, inconsistent with the other four NWA 4502 cratering shots, but this impact resulted in a mass loss of 11 grams, more than twice as much as either of the other two cratering impacts of the same target (Shots 160807 and 160809).

Disruption Experiments: The "strength" or "threshold collisional specific energy," Q^*_D, which is the energy required to disrupt the target such that the largest fragment has 50% of the target mass, is frequently used in modeling the effects of impacts on asteroids. We previously reported hypervelocity disruption measurements on nine ordinary chondrites [7], likely sampling the dominant type of asteroid in the inner half of the main belt, and carbonaceous chondrites, likely sampling the most common asteroids of the outer half of the main belt, an unweathered sample of the CV3 meteorite Allende [7], and three CM2 meteorites (Murchison and two Antarctic meteorites). The results, shown in Figure 1, indicate that the two NWA 4502 samples that disrupted have significantly lower strength under hypervelocity impact than the meteorites previously studied. However, we note that the other five NWA 4502 impact experiments, conducted under essentially the same conditions, resulted in cratering events, not disruptions, indicating that the two NWA 4502 targets used for shots 160806 and 160810 were significantly weaker than the NWA 4502 targets used in the other five shots. Even the sequence of three repeated impacts on the same target (Shots 160807, 160808, and 160809) did not weaken the target sufficiently to result in a disruption. Thus, it appears the flaw distribution in 160806 and 160810 was significantly different than the other five NWA 4502 targets.

Conclusions: Although the disruption of the NWA 4502 target in Shot 160806 might be explained by weaking from the prior impact (Shot 160805), the disruption in Shot 160810, which was not previously impacted, indicates that sample was significantly weaker under hypervelocity impact than the other NWA 4502 targets, likely a result of a different flaw distribution. While the momentum enhancement by cratering (β – 1) for NWA 4502 is about half that of river rocks, it is large enough to produce more deflection of the path of an asteroid than results from direct momentum transfer. The lower β value for Saratov, based on a single measurement, may result from Saratov's higher porosity.

References: [1] Syal, M. B et al. (2016) Icarus, 269, 50-61. [2] Britt, D. et al. in *Asteroids III*, U. of Az. Press, 485-500. [3] Flynn et al. (2016) *47th LPSC,* 1081. [4] Macke, R. J. (2010) Ph D. dissertation, University of Central Florida, Orlando, FL. 332 pp. [5] Holsapple, K. (2002) *NASA Workshop on Scientific Requirements for Mitigation of Hazardous Comets and Asteroids*, 47-52. [6] Housen, K. R. & K. A. Holsapple (2012), *43rd LPSC,* #2539. [7] Flynn, G. J. & D. D. Durda (2004) *Planet. Space Sci.,* 52, 1129-1140.

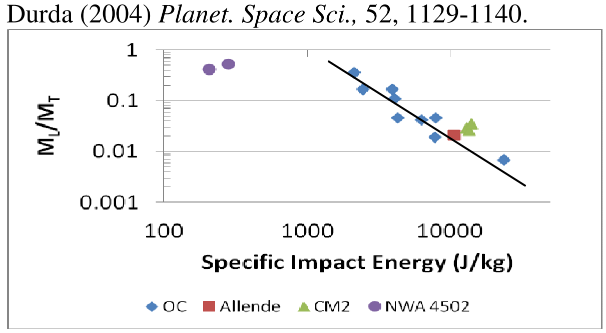

Figure 1: Plot of the specific kinetic energy of the projectile vs the ratio of largest fragment to target mass (M_L/M_T) for 9 ordinary chondrites, Allende, 3 CM2 meteorites and the 2 NWA 4502 disruptions.