RECOIL FROM CRATER EJECTA IN HYPERVELOCITY IMPACT OF HYDROUS AND POROUS TARGETS. G. J. Flynn¹, D. D. Durda², M. J. Molesky¹, B. A. May³, S. N. Cogram³, M. M. Strait¹ and R. J. Macke⁴, ¹Dept. of Physics, SUNY-Plattsburgh, 101 Broad St., Plattsburgh, New York, 12901 (george.flynn@plattsburgh.edu), ²Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder CO 80302, ³Alma College, Alma, MI 48801, ⁴Vatican Observatory, V-00120 Vatican City.

Introduction: The momentum change of an asteroid in response to impact cratering 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, $\beta$, given by:

$$\beta = \frac{(m_p v_p + p_r) / m_p v_p = M_v / m_p v_p}$$

where $m_p$ is the mass of the projectile, $v_p$ is the speed of the projectile, $p_r$ is the magnitude of the momentum of the crater ejecta opposite the recoil direction, $M_v$ is the mass of the target, and $v_v$ is the change in the speed of the target due to the impact.

Kinetic impactor deflection of an object on a collision course with Earth was described in a 2007 NASA Report to Congress as “the most mature approach and could be used in some deflection/mitigation scenarios, especially for NEOs [Near Earth Objects] that consist of a single small, solid body” [1]. However, a detailed knowledge of $\beta$ for the target NEO is particularly critical to the success of a deflection by kinetic impactor [2]. To constrain $\beta$, we have begun a series of hypervelocity cratering experiments on meteorites and analogs at the NASA Ames Vertical Gun Range (AVGR).

Thus far we have reported $\beta$ values for 13 dry ordinary and carbonaceous chondrite meteorite samples, including 7 samples of the Northwest Africa (NWA) 869 L3-6 ordinary chondrite, 5 samples of the Northwest Africa 4502 CV3 carbonaceous chondrite, and 1 sample of the highly-porous Saratov L4 ordinary chondrite [3]. All 7 of the cratering impacts into NWA 869 targets produced $\beta$ values in the narrow range from 1.82 to 3.81, with a mean of 2.71 ± 0.6. Four of the 5 cratering impacts into NWA 4502 targets produced $\beta$ values in the narrow range from 2.88 to 3.97, with a mean $\beta$ of 3.37 ± 0.5. The fifth NWA 4502 gave a remarkably different value of $\beta$ (11.72), well outside the range of the other four shots, suggesting the impactor in this shot struck a different material than the other four NWA 4502 impacts [3].

Since the NWA 4502 targets contained obvious weathering veins comparable in size to the 1/16” inch projectiles, we suggested that this anomalous $\beta$ value resulted from cratering into hydrous weathering material [3], since $\beta$ for a strengthless water target is reported to be 152, much larger than $\beta$ for even non-porous rocks [2]. If so, hydrous meteorites, and their parent hydrous asteroids, as well as comets might have remarkably different cratering recoil behavior than dry asteroids. Since hydrous, carbonaceous asteroids are common in the outer half of the main belt and are found among NEOs, a characterization of the recoil of hydrous asteroids is important to understand the dispersal of hydrous asteroid families and the deflection of potentially hazardous, hydrous NEOs.

Samples and Procedure: To test the proposition that the vaporization of water in hydrous targets causes “jetting” that significantly enhances the recoil in hypervelocity cratering we have conducted three cratering impacts into hydrous clay mineral targets of terrestrial serpentine. Serpentine was chosen because of its easy availability and because the the bulk of the crystalline material in the hydrous CI carbonaceous chondrite Orgueil consists of serpentine and montmorillonite [4]. We prepared three serpentine targets ranging in mass from 62 to 105 grams (Table 1) and determined the bulk and grain densities, allowing calculation of the porosity of each target. Two of the serpentine targets had moderate porosities, in the 17.0 to 18.8% range, comparable to the mean porosity of 22.2 ± 0.7% reported for hydrous CM chondrites, but significantly lower than the 34.9% porosity reported for CI meteorites [5]. As a comparison, we also measured $\beta$ for three more Saratov L4 ordinary chondrite targets, having comparable porosity to two of the serpentine targets. We measure both the porosity (Table 1) and the compressive strength (in progress) of our cratering targets because sensitivity testing shows that of the numerous parameters that can be included in modeling the recoil due to crater eject the predicted outcome is most sensitive to target strength and porosity [2].

To quantitatively determine the momentum transfer in a hypervelocity cratering event we suspended each serpentine target in front of a large rectangular grid in the vacuum chamber at the NASA Ames Vertical Gun Range. Each target was cratered by a 1/16” Al-projectile.

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>Bulk Vol. (cm³)</th>
<th>Grain Vol. (cm³)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>61.96</td>
<td>27.52 ± 0.15</td>
<td>22.86 ± 0.09</td>
<td>17.0 ± 0.6</td>
</tr>
<tr>
<td>104.72</td>
<td>46.58 ± 0.21</td>
<td>37.83 ± 0.06</td>
<td>18.8 ± 0.4</td>
</tr>
<tr>
<td>75.24</td>
<td>30.18 ± 0.08</td>
<td>29.21 ± 0.06</td>
<td>3.2 ± 0.3</td>
</tr>
</tbody>
</table>
A third serpentine sample was immersed in water for two days before the cratering shot to add liquid water to the target. The mass increased from 61.96 g to 64.89 g, indicating that the sample absorbed almost 3 g of water. However, we could not determine how much of this water was lost during the more than half-hour interval while the AVGR chamber was pumped to ~0.5 torr before the shot. This target disrupted with the first noticeable separation occurring 0.18 ms after impact. Soaking may have weakened the serpentine, resulting in the disruption rather than cratering. The two largest fragments have masses of 35.45 g and 25.87 g. We measured the recoil speed of each fragment and determined $\beta$ using the total momentum transferred to these two largest fragments.

**Conclusions:** The Saratov samples, with ~15.5% porosity have a mean $\beta = 2.08 \pm 0.56$, indicating that even moderately porous targets experience a significant enhancement in the recoil momentum due to the ejecta from hypervelocity cratering. The $\beta$ value for the high porosity (p = 18.8%) serpentine target ($\beta = 4.93$) is more than twice the $\beta$ value for the Saratov targets, which have comparable porosities, suggesting that the hydration of the serpentine target substantially enhances the momentum transfer by hypervelocity impact cratering. These measurements on porous and hydrous targets provide important data to validate hydrocode modeling of the recoil in cratering impacts.

**References:**