METEOROID BOMBARDMENT AND BLAST EXPERIMENTS ON ASTEROIDS. E. Asphaug[1], J. Colwell[2], R. Dissly[3], K. Kanizay[3], V. Petr[4], and D.J. Scheeres[5] • [1]Earth Sciences Department, University of California, Santa Cruz, CA 95064 (asphaug@es.ucsc.edu), [2]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder CO, [3]Ball Aerospace and Technologies Corp., Boulder, CO, [4]Dept. Mining Engineering, Colorado School of Mines, Golden CO [5]Dept. Aerospace Engineering, U. Michican, Ann Arbor, MI

Introduction: From the accretion of planetesimals 4.6 billion years ago to the spallation of meteorites from their parent bodies, the impact process has left no bit of planetary matter untouched. The *in situ* analysis of simple blast experiments on asteroids can therefore provide a foundation for understanding accretion and the delivery of meteorites – topics central to the origin of planets – and can bring resolution to a fundamental debate regarding the basic mechanics of meteoroid bombardment and regolith behavior on small bodies.

Large Crater Puzzles: Original studies of small body cratering [1,2] had difficulty explaining the existence of Stickney on Phobos and comparably large craters on the small moons of the outer solar system. Small bodies can evidently sustain huge craters despite the conclusion of strength scaling that the impactor responsible for Stickney would have catastrophically disrupted Phobos. Models [3] and later analyses [4] showed that Stickney formed in the gravity regime, but as soon as this conclusion gained acceptance, it faced its own obstacle. Asteroid Mathilde's craters – the largest being >0.6 times the target diameter – exhibited neither ejecta deposits, nor any evidence of strength control or impact overprinting [5]. Two models have been proposed to explain these craters, with very different implications for asteroid structural geology, planetesimal evolution, accretion, and even strategies for NEO mitigation [6]. In many ways asteroid cratering science is back to "square one".

Compaction Cratering: Housen et al. [7,8] advocate compaction of highly porous, somewhat cohesive media as an explanation for the large craters on asteroid Mathilde. If an asteroid is significantly porous and compactible at whole-body scales, then one might expect craters at small scales to form under even more compressible conditions. The experiments proposed for *Deep Interior* surface pods, described below (see also abstract by Scheeres et al., *Asteroid Surface Science with Pods*) will test this conjecture directly.

Housen et al. [7,8] utilize centrifuge impact experiments performed at 1 to 500 G in testbeds cured from a mixture of quartz sand, expanded perlite, fly ash and water. Compressive strength for this material is about 2×10^5 dyn/cm^2 [8]. Note that this measured strength is bracketed by characteristic gravitational stress $\rho g D$ for the 500 G experiments ($\sim 10^6$ dyn/cm^2) and for the 1 G experiments ($\sim 10^4$ dyn/cm^2). Our interpretation is that cohesion alone, rather than gravity scaling to the size of Karoo, could explain the differences between the 1 G and 500 G experiments. When $\rho g D$ exceeds cohesion, mobilized crater materials can be expected to initiate a downward-accelerated collapse, turning what would have been a ~5 cm crater into a ~7 cm crater at 500 G and inhibiting the launch of ejecta. We don't argue that compaction is not taking place in these high-G experiments in weakly cemented porous silicates. But we question whether this compaction has relevance to an asteroid like Mathilde.

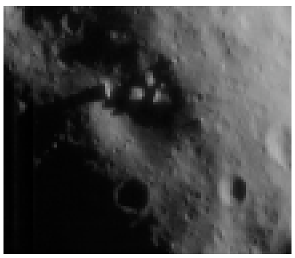
Cohesion: On the other hand, one can argue that the use of cohesive silicate powders in a terrestrial testbed is appropriate. The bonding energy available in a granular volume scales as the total contact area divided by the total mass, so cohesion scales as r^{-1} for grains of radius r. (For size distributions of $r^{-□}$, cohesion will increase with □ and be dependent on packing.) Consider a bed of dune sand ($r \sim 300$ μm) transported to a 1 km asteroid (g=10^{-5}G), and contemplate a terrestrial testbed where the ratio of cohesion to gravitational stress is made comparable. If cohesion scales as $1/r$, then to simulate the behavior of sand on an asteroid requires a hyperfine powder with $r \sim 10^{-5} \cdot r_{sand} \sim$ 0.003 μm. Xerographic toner has diameter 12.7 μm, and although ~4000 times less cohesive than what we envision, can easily sustain scarps of arbitrary (or undercut) slope, can exhibit fracture and other kinds of "geological" behavior, and is relatively compactible.

We don't suggest that asteroids are hyperfine powders. We merely illustrate that in a low-gravity environment, the relatively high strength of cohesive forces between particles means that even macroscopic grains in the regolith can support unusual structural behavior including scarps and fractures (perhaps even as seen on Eros), and may crater in strange ways.

Impact experiments at much lower velocities in microgravity have shown a strong dependence of cratering on grain size distribution and grain shape [9]. Both strongly affect the number of contact points between particles and the relative strength of cohesion, supporting the idea that cohesion plays an important role in cratering in microgravity environments.

It is also worth noting that separate impact experiments [10] into fluffed (ρ=1.1 g/cm^3) powdered pumice targets yield substantially different results than [7,8], exhibiting a gravity-regime response with about the same scaling exponent as for dry sand, but with cratering efficiency about half as great. It is unknown where the differences lie, but the choice of material analog seems important. It is potentially significant that the measured cohesion of the testbed material of [7,8] is <□*gD* for the 500 G experiments (those scaled for large craters on Mathilde) and >□*gD* for the 1 G experiments.

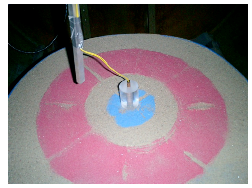
Asteroidal Evidence: Careful attention needs to be paid to the testbed, and perhaps the only way to solve the problem rigorously is to perform the experiments *in situ*. This is simpler than it sounds. For one thing, Nature has provided her own scaling experiments, at large [11] and small scales. For another, making a crater at an asteroid with standard explosives can be done without significant added burden to an orbital mission (see abstract by Asphaug et al., "Exploring Asteroid Interiors").



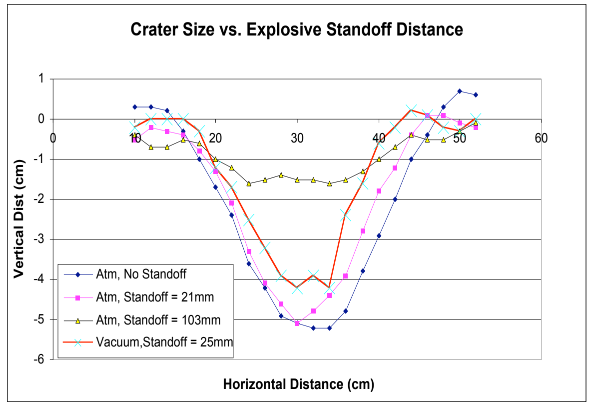
Above is an image of asteroid Eros (NEAR Image 0136819148). Here, four ~100 m fragments of an ejecta block appear to rest in the ~700 m diameter secondary crater they created. The odds of this being a chance association are minuscule; most likely it is the record of a rock of known mass ($\sim 2 \cdot 10^{10}$ kg) impacting at known speed ($v_{orb} \sim 10$ m/s). The impact split the rock into 4 major pieces, from which we can constrain soil compaction and rock strength. Gravity scaling for dry sand predicts a crater about half this diameter, perhaps because momentum-driven coupling is more efficient than hypervelocity (energy-driven) coupling. Alternatively, regolith bulk density may be less than the dry sand assumed in this calculation. Or the impact speed could have been up to twice as great as assumed ($\sim v_{esc}$). It is certainly not the manifestation of an impact into a hard rocky surface.

It has also been noted [5] that small craters are absent at small (~10 m) scales on asteroid Eros. It has been postulated that this is due to the absence of small impactors [12]. One may also speculate that it represents an inefficiency of cratering mechanics at small scales, due to an incredibly porous surface which absorbs ~10 cm impactors without a trace.

Experiments on Asteroids: In this era of diverging hypothesis, further investigation is required. Our proposal, as part of the *Deep Interior* Discovery mission concept, is to perform a series of simple, well-calibrated, *reproducible* blast experiments on the surface of one or more asteroids. Each blast experiment will be imaged in detail by the orbiting spacecraft to watch crater formation in action. From this one can assess regolith properties such as cohesion, porosity, and particle size distribution, and determine the governing mechanics and kinematics of ballistic ejecta.



Surface explosion testbed at Colorado School of Mines (left); preliminary tests of effect of vacuum and standoff on crater diameter (below).



To help define and plan the proposed spacecraft-imaged surface experiments, and to set the stage for the interpretation of acquired mission data, we have begun a laboratory program at the Colorado School of Mines making scaled explosive tests on various target media. To date, we have run multiple tests in sand, investigating the effects of both vacuum and standoff distance between the charge and the target surface. While vacuum has little effect on the resulting crater dimensions when the explosive charge is in contact with the target surface, the excavated crater volume becomes rapidly smaller as the standoff distance grows longer than the charge size. These preliminary results indicate, for example, that designing the *Deep Interior* surface experiment with the charge in contact with (or a known distance above) the surface will be critical in evaluating blast experiments on asteroids.

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