ASTEROIDS ON THE MOON: PROJECTILE SURVIVAL DURING LOW VELOCITY IMPACT. P. A. Bland[1,2], N. A. Artemieva[3], G. S. Collins[1], W. F. Bottke[4], D. B. J. Bussey[5] and K. H. Joy[2,6]. [1]Impacts & Astromaterials Research Centre (IARC), Dept. Earth Sci. & Eng., Imperial College London, SW7 2AZ, UK. E-mail: p.a.bland@imperial.ac.uk. [2]IARC, Dept. Mineralogy, Natural History Museum, London SW7 5BD, UK. [3]Institute for Dynamics of Geospheres, Russian Academy of Sciences, Leninsky Prospect 38/6, Moscow, Russia 117939. [4]Southwest Research Institute, 1050 Walnut St, Suite 400, Boulder, CO 80302, USA. [5]The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, MP3-E180, Laurel, MD 20723, USA. [6]UCL/Birkbeck Research School of Earth Sciences, UCL, Gower Street, London, WC1E 6BT, UK.

Introduction: Asteroids are being constantly delivered to the Earth's surface, but any attempt to understand them as geological bodies is severely limited by impact processing. Although our atmosphere is effective at significantly reducing surface impact velocities for smaller asteroids (e.g. [1]), allowing us to study meteorites with diameters of less than a few metres, larger objects strike the surface at close to their cosmic velocity. The lower limit for pre-atmospheric impacts at Earth is 11.2 km/s (Earth escape velocity). Principally due to these high velocities, solid projectile material is extremely rare at terrestrial craters >1-2 km. However, in addition to velocity, impact angle can have a profound effect on projectile survival [Pierazzo & Melosh 2000]. In high velocity impacts, only at low angles does a significant proportion of the projectile remain in the solid phase, but even at 15°, for typical terrestrial impacts, shock pressures are high, with 90% of material at >50 GPa [2]. The end result is that although we may see the geochemical signature of projectile melt at an impact site, a more detailed study of the impactor (e.g. of large-scale structural or compositional variation) is impossible.

Lacking an atmosphere, there is no mechanism to decelerate impactors on the Moon. But minimum impact velocity (related to its escape velocity and the gravitational effect of the Earth at lunar distance) is much lower: 2.78 km/s. Projectiles of all sizes are therefore capable of striking the lunar surface at velocities far lower than is possible on Earth. We chose to explore the effect of these low velocity impacts on projectile survival, to constrain the proportion of the impactor that experiences melting, the proportion that is essentially unaltered by the impact (shock pressures <10 GPa), and the fraction of the object that remains localized within the resulting crater. The aim is to derive an estimate for the number of lunar craters which contain substantial asteroidal material.

Results and Discussion: We have modelled lunar impacts at 3 km/s, 5 km/s, and 7 km/s, for impact angles of 15°, 30°, 45°, 60° and 90°. In the high-angle 7 km/s scenarios we observe some projectile melting: at 60°, 18% melting, and at 90°, 32% melting. In all other scenarios >90% of the projectile remained in the solid phase (although fragmented to varying degrees). In addition, a significant fraction of the projectiles experienced shock pressures <10 GPa e.g. ~65% of the projectile at 3 km/s and 45°, 25% at 5 km/s and 45°, and 12% at 7 km/s and 45°.

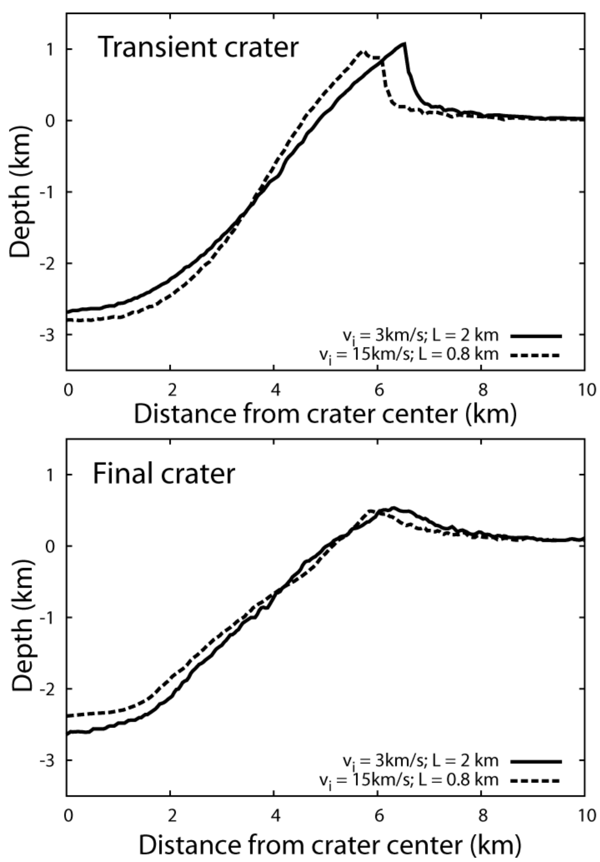
Does the projectile material remain close to the source crater, or is it widely dispersed? Our results (see Table 1) indicate that in the majority of cases >50% of the projectile remains within the crater.

Impact angle \ impact velocity	**3km/s**	**5km/s**	**7km/s**
90°	0.92	0.82	0.79
60°	0.73	0.68	….
45°	0.59	0.52	0.42
30°	0.31	0.23	0.19
15°	0.11	0.07	0.05

Table 1. Proportion of projectile material (by mass) remaining within the crater for various impact angles and velocities.

How common are these events? In excess of 50% of the projectile remains in the crater for angles between 45° and 90° (ie. 50% of all impacts), and for all modelled velocities. Objects impacting the Moon at 2-4 km/s account for 0.18% of all lunar impacts; 1.2% of objects impact at 4-6 km/s; and 3.8% impact at 6-8 km/s [3,4]. Therefore, we can say that ~2.6% of lunar craters (ie. approximately half of all impacts between 2 km/s and 8 km/s) will contain >50% of the impacting object, and that this material will have experienced minimal melting. As discussed above, a sizeable fraction of the surviving projectile in these craters will be essentially unaltered, experiencing shock pressures <10 GPa. Based on the lunar mare and highland crater size frequency distributions [5], and the overall proportion of mare and highland crust, we can estimate approximate numbers of craters formed under the conditions described above (ie. >50% of the impactor remaining within the crater, and minimal melting). For the highlands, we would anticipate >600 craters >10 km in size, and 5-10 >100 km in size, and for the mare ~70 >10 km in size, and 5 >50 km in size.

Are there any morphological characteristics peculiar to craters formed at low velocity that may help in their identification? Crater scaling theory suggests that impact crater size is related to a combination of impactor mass (size) and velocity. Thus, the same size crater may be formed by a smaller faster projectile, or a larger slower projectile. However, the effect of velocity on crater morphology is not well understood. Numerical models of the formation of an ~10 km diameter crater on the Moon suggest that if the crater is formed by a large, low velocity impactor the transient crater is broader and shallower than would be the case for a smaller, faster projectile (Figure 1). Subsequent crater collapse reduces the difference between the final crater profiles because more collapse occurs when the transient crater is deeper with steeper rim walls. However, these results suggest that the breccia lens thickness, and the degree of rim wall slumping, which would tend to mix projectile and target material, is less in a lower velocity impact. As well as preserving an impactor-rich breccia lens, this may offer a possible means of identifying low velocity craters.



In addition, laboratory-scale oblique impact experiments and 3D numerical modelling studies suggest that in oblique impacts the transient cavity is very asymmetric in the earliest stages of formation and progressively loses its asymmetry as it grows, due to geometric spreading. The asymmetry of the final crater, therefore, depends not only on the angle of impact, but also on the size of the crater in relation to the size of the projectile. Observable asymmetry may occur for moderately oblique (30-60°) impacts if the crater is only a few times larger than the projectile, which is the case when the impact velocity is extremely low. Hence, it is possible that moderately oblique, low velocity impacts on the Moon may form craters with asymmetric structure related to impact direction.

In terms of the overall mass of meteoritic material at the lunar surface, how significant are craters formed at low velocity? There is ~1-2% of meteoritic material present in lunar regolith, mostly from micrometeorite and 'small' meteorite impact [6,7]. Assuming a regolith thickness of 10-20m, this would suggest ~10^{16} kg of comminuted meteoritic material in the lunar regolith. Our low velocity projectiles produce relatively small craters for their size: a 5 km/s impact which produces a 100 km crater will require an impactor of ~10^{15} kg mass. Given the expected number of craters, it is apparent that the total mass of material is significant.

What could we expect to find if we were to search one of these craters? Although shock pressures are low, strain values are extremely high. Materials are typically treated as totally damaged if tensile strain exceeds 0.01-0.1. The values we observe are much higher, so clearly we are looking at craters which contain unmelted asteroidal material, and relatively unshocked material, but not intact asteroids. Unfortunately, it is impossible to define accurately a size frequency distribution for fragments in these cases.

Conclusions: Our analysis suggests: 1) numerous low velocity impact events will be recorded on the Moon; 2) projectile material will be relatively unshocked, and largely contained within the crater; and 3) the total mass of asteroidal material associated with these events is significant. We are currently exploring whether these craters are detectable by remote sensing.

References: [1] Bland P.A. and Artemieva N.A. 2006. *MAPS* 41: 607-631. [2] Pierazzo E. and Melosh H.J. 2000. *MAPS* 35: 117-130. [3] Bottke W.F. et al. 2002. *Icarus* 156: 399-433. [4] Bottke W.F. et al. 1994. *Icarus* 107: 255-268. [5] Neukum G. et al. 2001. *Space Science Reviews* 96: 55-86. [6] Wasson J. T., Boynton W. V. and Chou C-L. 1975. In *The Moon* 13: 121-141. [7] McKay D. S. et al. 1991. In *Lunar Sourcebook* (ed. G. Heiken et al.), pp. 285–356. Cambridge Univ. Press.