MODELING LOW VELOCITY IMPACTS: PREDICTING CRATER DEPTH ON PLUTO

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The New Horizons mission is due to fly-by the Pluto system in Summer 2015 [1] and provides the first opportunity to image the Pluto surface in detail, allowing both the appearance and number of its crater population to be studied for the first time. Bray and Schenk [2] combined previous cratering studies and numerical modeling of the impact process to predict crater morphology on Pluto based on current understanding of Pluto's composition, structure and surrounding impactor population. A synthesis of these findings will be presented at the Planetary Crater Consortium (August 2014); the additional results from hydrocode simulation of low velocity impacts are presented here.

Modeling Approach: The necessity for hydrocode modeling as part of this investigation is due to observations of secondary cratering (low velocity, high angle) and laboratory experiments of impact at low velocity being at odds: observations of secondary craters show that these low velocity craters are shallower than would be expected for a hyper-velocity primary (e.g.,[3]). Conversely, gas gun work [e.g., 4, 5] has shown that crater depth increases as impact velocity decreases. The average impact velocity in the Pluto system is ~ 2km/s, making this an important factor.

The hydrocode simulations performed as part of this work utilized the iSALE hydrocode [*6*], designed to simulate the impact process. Various combinations of impactor size and velocity were performed to produce simple craters on a Pluto-mass body. See [2] for material model details.

Modeling Results: With increasing impact velocity, a projectile will produce wider and deeper craters (Figure 1A), as expected on the basis of much previous work [e.g., *[7]* and references therein]. The depth-diameter ratio (d/D, Figure 1B) has a complex progression with increasing impact velocity. Impacts faster than 2 km s^{-1} lead to smaller d/D ratios as impact velocity increases, in agreement with previous studies [e.g., 4,5]. Conversely, decreasing impact velocity from 2 k m s^{-1} to 300 m s^{-1} produced smaller d/D.

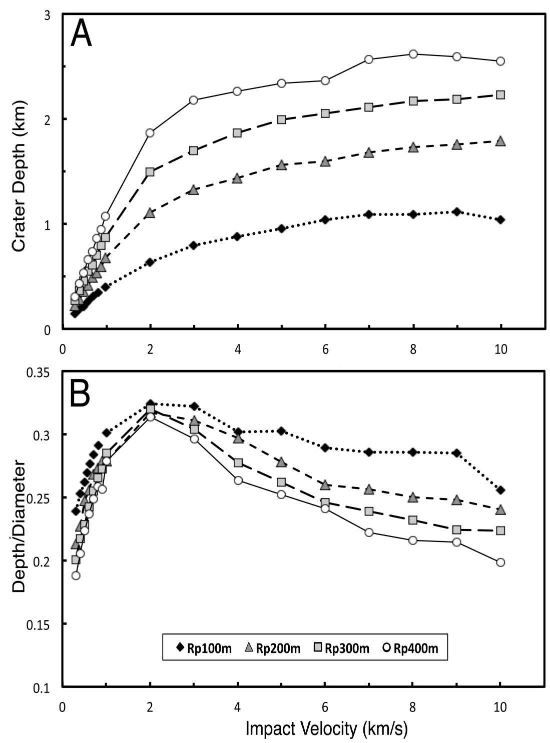

Figure 1: Simulation results: comparison of impact velocity and crater depth for the simple craters produced in this work. Rp refers to projectile radius. A) crater depth, B) depth-diameter ratio. These results suggest that lower impact velocities generally produce relatively deeper craters (higher d/D ratio), but that a minimum velocity can be reached below which the depth of craters becomes shallower as velocity decreases still further. Although this inflection point occurs at an impact velocity of 2 km/s in this work, variations in the model parameters could produce an inflection in the d/D trend at a different velocity.

Discussion: If d/D does have a maximum value for a specific impact velocity and decreases as impact velocity increases/decreases away from this optimum value (Figure 1B), it would explain the apparent contradiction between the observations that lower velocity impacts can produce deeper primary craters [e.g.,*8, 5*] and that secondary impacts produce relatively shallow craters [e.g., *3*]. The two-part trend in d/D with impact velocity might be the result of variations in projectile-target coupling: for impact velocities above the sound speed of the target (~ 3 km s^{-1} in this case), the point-source assumption of crater scaling rules can be applied and the coupling of projectile and target becomes poorer as impact velocity increases [c.f. 9]. For impact velocities below the sound speed of the target, the release of energy from the impact is no longer approximated as a point-source, and standard crater scaling rules no longer apply. Relation to sound speed might explain why the change in trend noted in Figure 1B occurs close to impact velocities of 3 k m s^{-1}. Instead, this work notes this 'inflection point' at impact velocities of 2 km s^{-1}. Deviation of the inflection point from the sound speed of the material might be the result of the hydrocode model parameters used for these simulations. The result of maximum d/D occurring for an impact velocity of 2 km s^{-1} is thus presented here as an example that a velocity-dependent inflection might occur, not as a firm suggestion of the exact velocity at which maximum d/D would be produced.

Predictions for Pluto: Crater Depth and Depth-Diameter Ratio

Complex craters experience the most collapse, and thus have lower d/D, in weak targets and in high gravity. Pluto's complex craters are thus expected to be shallower than those on rocky bodies, but not as shallow as complex craters on icy bodies of greater gravity such as the Gailean satellites. Based on its gravity and icy crust, simple crater depth on Pluto is expected to be more akin to that of craters on small icy satellites than craters on rocky bodies (this implies craters 30-40% shallower than simple craters on terrestrial planets [*10*]).

However, Figure 1B shows that depth-diameter ratio (d/D) increases as impact velocity decreases from 10 to 2 km s^{-1}. This suggests that the low mean impact velocity of 2 km s^{-1} in the Pluto system [c.f. 11] might produce craters deeper than those on other small icy bodies. The change in d/D with impact velocity is not straightforward however, and there are separate d/D-velocity relationships for impact velocities less than and greater than 2 km s^{-1} (Figure 1C). As 2 km s^{-1} is the predicted mean impact velocity, it is probable that impacts will also occur at velocities below 2 km s^{-1}, perhaps producing lower d/D craters (Figure 1C) alongside relatively deep craters formed by ~ 2 km s^{-1} impacts. The complex relationship between impact velocity and crater depth for impacts occurring between 300 m s^{-1} and 10 km s^{-1} suggests that there might be a larger range of 'pristine' crater depths on Pluto than on bodies with higher mean impact velocity.

References: [1] Stern, A. S. (2008). Space Science Reviews 140:3-21. [2] Bray and Schenk (2014). Icarus, In Press. [3] Bierhaus, E.B. et al. (2005). Nature 437:1125-1127. [4]Cintala, M. J. (1979). 10th LPSC., Proc. Vol 3. pp.2635-2650. [5] Barnouin, O.S. et al. (2011). LPSC 42, Abstract # 2258. [6] Collins, G. S., et al. (2004). Meteoritics and Planet. Sci. 39:217-231. [7] Melosh, H. J. (1989). Impact cratering: New York, Oxford University Press. [8] Schultz, P. H. (1988) in *Mercury*, Univ. Arizona Press, pp. 274–335. [9] Baldwin, R. B. (1963). The measure of the Moon. University of Chicago Press. [10] Schenk, P.M. (1989). J. Geophys. Res. 94:3813-3832. [11] Zahnle, K., et al. (2003). Icarus 163, 263-289.