Impacts into Pluto: The effect of a Nitrogen ice surface layer. A. J. Trowbridge[1*], H. J. Melosh[2], and A. M. Freed[3], Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, Indiana 47907, ([*]atrowbr@purdue.edu).

Introduction: Presently, very little is known about the surface of Pluto. However, on July 14th, NASA's *New Horizons* mission will begin its closest approach to Pluto and return the first high resolution images of its surface. Despite the lack of observational evidence, Pluto, like other icy planetary bodies, will undoubtedly have impact craters, remnants of collisions from neighboring bodies in the Kuiper Belt. The Long Range Reconnaissance Imager (LORRI) on New Horizons has a maximum resolution of 0.07 km/pixel [1]. At this resolution, craters larger than ~1 km can be resolved [1]. With the ability to image a large range of craters, New Horizons is expected to provide insight into the size frequency distribution (SFD) of Kuiper Belt Objects (KBOs) by scaling the observed crater SFD back to impactor SFD.

However, crater-scaling laws (e.g., impact energy to diameter ratios) are not well defined for low velocity impacts into icy surfaces; this is especially true for crater depth scaling relationships. Schnek [2] showed that crater depth-to-diameter ratios (d/D) varied widely among the icy satellites, without a clear correlation to surface gravity or impact velocity. This may indicate that rheologic strength, which may vary widely amongst icy bodies, may play an important role in the evolution of crater morphology. The possible existence of a nitrogen layer on Pluto, as revealed by spectral data [1], may further influence the manner in which craters form in its surface. The effect of a nitrogen ice layer on crater formation is currently not well understood. In order to produce accurate scaling laws for Pluto, this effect needs to be investigated. Thus, to better understand the relationship between SFD of craters on Pluto and the distribution of KBOs, we explored the effect of nitrogen ice on crater development using hydrocode simulations of low velocity impacts into water ice body covered by a thin (up to 3 km) layer of nitrogen.

Methodology: To simulate impact formations, an equation of state (EoS) and a strength model needed to be developed for nitrogen. We used the Tillotson EoS [3] to fit to known Hugoniot data for low temperature liquid nitrogen [4, 5, 6], but assumed an initial density of solid nitrogen to provide a viable EoS for solid nitrogen (William Nellis, personal communication). Figure 1 shows that the our Tillotson EoS fits Hugoniot data well.

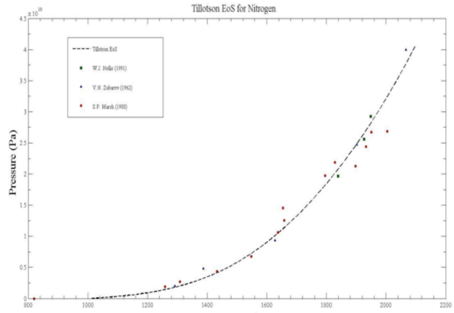

Figure 1. *Tillotson EoS fit to Hugoniot data for low temperature liquid nitrogen.*

Using methane [7] as a proxy of the unknown strength properties of solid nitrogen, we employed the Lundborg equation [8] to produce a strength model for nitrogen. Strength properties of methane were choosen for two reasons: (1) nitrogen is likely to have similar strength properties as methane, because the two have similar crystal structures and molecular bonds [7, 9] and (2) the lack of experimental data for the strength of nitrogen ice. Once constructed, the Tillotson EoS for nitrogen and strength model were implemented into iSALE to simulate impacts on Pluto.

iSALE simulations. In this work, we used the iSALE-2D shock physics code [10], which is based on the SALE hydrocode solution algorithm [11]. To simulate hypervelocity impact processes in solid materials, SALE was modified to include an elasto-plastic constitutive model, fragmentation models, various EoS, and multiple materials [12, 13]. More recent improvements include a modified strength model [14] and a porosity compaction model [10, 15].

Models assumed axisymmetry and simulated a spherical, water ice projectile impacting at 2 km/s, typical for a KBO [2, 16]. We used a surface gravity of 0.658 m/s^2 and a surface temperature of 33 K. Models were constructed with a nitrogen ice layer (initial density of 995 kg/m^3) overlaying an water ice layer (initial density of 998 kg/m^3). Since the thickness of the nitrogen ice layer is not well-constrained, we we varied the thickness of from 0 to 4 km (the expected range for thicknesses of a nitrogen layer based on [1]). Impactor diameters (D) was varied between 1-10 km.

Scaling laws from iSALE simulations. The concept for scaling relationships comes from the idea that crater development, including the diameter of the transient crater (λ), can be defined as a simple function of three dimensionless parameters, π_2, π_3, π_4 associated with gravity, strength, and the impactor-target density ratio, respectively [10, 17]. The transient crater is defined as the crater at the end of excavation, but prior to collapse, identified by the formation of kinks at the bottom of the excavation plume.. The diameter of the transient crater is calculated as the width that overlaps between the horizontal plane defined by the unexcavated ground and the opening of the crater. Figure 2 shows the transient crater visually.

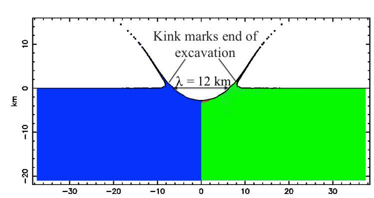

Figure 2. *A snapshot of a transient crater formed. The transient crater (λ) forms when kinks appear at the base of the excavation plume. The diameter of the transient crater is measured as the width between ejecta plumes at the overlap of the horizontal plane defined by the unexcavated ground and the opening of the crater.*

iSALE results of transient crater diameters as a function of impactor diameters for different rheological models were plotted on a log-log scale and were fitted with a power law to determine new scaling laws. This was done for each thickness of nitrogen ice, for a range of impact diameters (1-10 km) to investiagate the effect nitrogen ice has on scaling laws.

Preliminary Results: We modeled a water ice projectile that is 2 km in diameter that impacts at a velocity of 2 km/s [1, 16] into a nitrogen ice layer with thicknesses of varying from 0 to 4 km. The left side of Figure 3 shows the result of a 2 km water ice projectile impacting a pure water ice surface (dark grey material), while the right side shows the result of the same simulation but with a 3 km nitrogen ice layer (tan region) above the water ice.

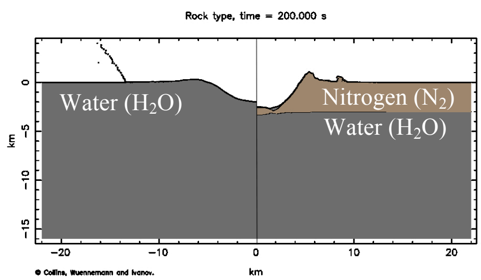

Figure 3. Plot showing *crater morphologies for two separate runs. (Left) shows a 2 km water ice projectile impacting a water ice target at 2 km/s. (Right) shows a 2 km water ice projectile impacting a water ice target with an overlying, 3 km thick, nitrogen ice layer at 2 km/s.*

With the presence of a 3-km-thick nitrogen ice layer, the impact forms a deeper crater with a smaller diameter. This result is expected given that there is a weaker strength material (nitrogen), overlying a stronger material (water). The weakness of the nitrogen ice layer also leads to the development of a central mound. For a thinner nitrogen layer of 0.5 km (Figure 4), nitrogen ice still affects the crater (d/D) ratio. Although the depth from horizontal remains consistant, the overlying nitrogen ice layer folds back upon itself and develops a scarp, which raises the rims of the crater and limits the diameter of the crater. It is evident from our first simulations that nitrogen ice affects the (d/D) ratio, therefore, normal scaling laws might not be appropriate for Pluto.

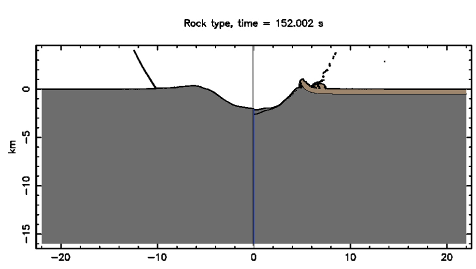

Figure 4. *Crater morphology for two separate runs. (Left) 2 km water ice projectile impacting a water ice target at 2 km/s. (Right) 2 km water ice projectile impacting a water ice target with an overlying, 0.5 km thick nitrogen ice layer at 2 km/s. Notice on the right, the nitrogen ice folds back upon itself developing a scarp.*

Discussion: The next step is to complete the servay of simulations for a range of impact diameters (1-10 km). After which we will produce crater-scaling laws for each thickness of nitrogen ice (0.5, 1, 2, 3, and 4 km). Doing so will allow us to produce a usable tool to determine the SFD of KBOs from imaged craters on Pluto.

Another possible benefit from this work would be a constraint on basin relaxation. The depth-diameter ratios observed for unrelaxed basins is crucial for determining practical basin relaxation models [16].

A potential complication for this method is that the surface layer of nitrogen ice might be porous. The collapse of Pluto's atmosphere is a debated topic, but if the atmosphere were to freeze and deposit on the surface as snow, the layer of nitrogen ice might be very porous. The increase in porosity would further weaken the nitrogen ice layer thereby causing a possible discrepancy between our results and observation.

References: [1] Stern, S. Alan, Simon Porter, and Amanda Zangari. (2015). *Icarus*, 250, 287-93. [2] Schenk, Paul M. (1989). *J. Geophys. Res. Journal of Geophysical* Research, 94.B4, 3813. [3] Tillotson, J.H., (1962). Metallic equations of state for hypervelocity impact. General Atomic Report GA-3216, General Atomic, San Diego, CA. [4] Nellis, W. J., H. B. Radousky, D. C. Hamilton, A. C. Mitchell, N. C. Holmes, K. B. Christianson, and M. Van Thiel. (1991). *J. Chem. Phys. The Journal of Chemical Physics* 94.3, 2244. [5] Zubarev, V. N. and Telegin, G. S., (1962). Dokl. Akad. Nauk SSSR 142, 309 [Sov. Phys. Dokl. 7, 34 (1962)]. [6] Marsh, Stanley P. 1980. *LASL Shock Hugoniot Data*. Berkeley, CA: U of California. [7] Haynes, William M. (1971). *Journal of Physics and Chemistry of Solids,* 32.4, 791-97. [8] Lundborg, N., (1968). Strength of rock-like materials. Int. J. Rock Mech and Mining Sci. 5, 427–454. [9] Eluszkiewicz, Janusz, and David J. Stevenson. (1990). *Geophysical Research Letters Geophys. Res. Lett.*, 17.10, 1753-756. [10] Wünnemann, K., G.S. Collins, and H.j. Melosh. (2006). *Icarus*, 180.2, 514-27. [11] Amsden, A., Ruppel, H., and Hirt, C. (1980). *Los Alamos National Laboratories Report*, LA-8095:101p. [12] Ivanov, B.A., D. Deniem, and G. Neukum. (1997). *International Journal of Impact Engineering*, 20.1-5, 411-30. [13] Melosh, H. J., E. V. Ryan, and E. Asphaug. (1992). *Journal of Geophysical Research*, 97.E9 [14] Collins, G. S., Melosh, H. J., and Ivanov, B. A. (2004). *Meteoritics and Planetary Science*, 39:217--231. [15] Collins, G.s., H.j. Melosh, and K. Wünnemann. (2011) *International Journal of Impact Engineering* 38.6: 434-39. [16] Kamata, Shunichi, and Francis Nimmo. (2014). *Journal of Geophysical Research: Planets* [17] Holsapple, K.R., Schmidt, R.M., (1987). *J. Geophys. Res.* 92, 6350–6376.