IMPACT INDUCED MELTING AND VAPORIZATION ON ICY PLANETARY BODIES. R. G. Kraus[1], S. T. Stewart[1] , [1]Harvard University, Department of Earth and Planetary Sciences, 20 Oxford Street, Cambridge, MA 02138, U.S.A. (rkraus@fas.harvard.edu).

Introduction: Melting of H_2O ice during planetary impact events is a widespread phenomenon. As relatively low shock pressures are required to melt ice, large volumes of liquid may be produced. Depending on the size of the event, the liquid water may persist for long time scales. However, knowledge of the volume and spatial distribution of liquid water produced from an impact is necessary to draw conclusions about the longevity of the liquid water on a planetary surface.

Using hydrocode simulations we calculate the volume of ice that is melted and vaporized for a wide range of impact conditions and derive scaling laws as a function of initial temperature, projectile size, impact velocity, and impact angle. For many reasons, it is important to know not only how much melt is produced but the spatial distribution of the melt after crater formation. As the current simulations were only run for times relevant to decay of the primary shock wave, we compared our melting data with full crater formation simulations, performed by Senft and Stewart [1]. They observed a concentration of melt at the center of the final crater in the shape of a "hot plug", as compared to a melt sheet. We determine the fraction of shock melted H_2O left within the final crater.

Numerical Simulations: We simulate impacts of H_2O projectiles into half spaces of pure H_2O using CTH, an Eulerian hydrocode developed at Sandia National Laboratories [2]. The 5-phase EOS for H_2O [3] used in these simulations has been experimentally validated in the pressure and temperature range most relevant to melting and vaporization of H_2O [3]. Two dimensional simulations were performed using a high resolution computational mesh of 40 cells per projectile radius. A resolution of 20 cells per projectile radius was used in the three dimensional simulations. The difference in resolution creates an approximately 10% difference in the calculated melt volumes. For more details of the numerical simulations see [4].

We modeled impacts at velocities from 1-80 km/s, initial projectile and target temperatures from 50-300 K (representing ice and surface oceans) and impact angles from 30-90 degrees. Impactor size, 1 km diameter, was not varied as gravity and strength were not taken into account in these calculations; consequently the hydrodynamic equations scale with impactor size.

Analysis: Ten thousand Lagrangian tracer particles were used to track the thermodynamic properties as a function of position and time within the icy body. Tracer resolution tests were performed and suggest less than 5% uncertainty in the melt volumes is created by the current tracer configuration.

Melt and vaporization volumes were determined using the critical entropy method [5]. This method is based on calculating the volume of material that is shocked to or above the critical entropies for incipient melting, complete melting, incipient vaporization, and complete vaporization. This method assumes that release to the reference pressure from the shocked state is isentropic. For this series of numerical experiments we have chosen the reference release pressure to be the triple point pressure of water (611 Pa), a widely applicable reference state.

Shock Induced Melting: We calculate the normalized volume of H_2O that has been melted and vaporized as a function of impact velocity and temperature (Figure 1). Note that lower velocities deviate from the power law fits due to the non-negligible shock pressure required to get to the melting point [6].

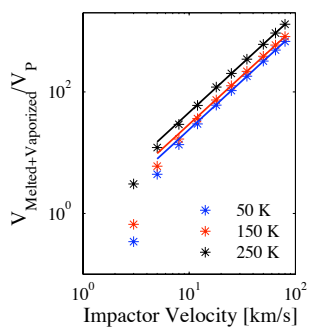

Figure 1. Scaled volume of H_2O ice that has been melted (including partial melt) and vapor. Fits are valid from ~8-80 km/s. V_P is the impactor volume.

Oblique Impacts: As seen by Pierazzo et al [7], the amount of impact melt decreases significantly with shallower angles of impact. Figure 2 presents results for a series of oblique impacts at a range of impact velocities (12, 25, 65 km/s) and angles (90, 45, 30 degrees).

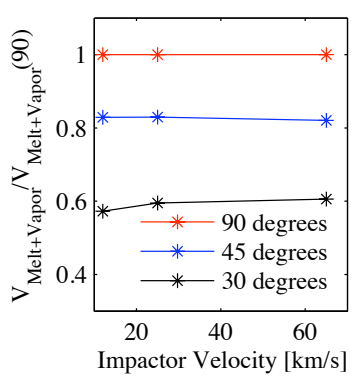

Figure 2. Scaled volume of material that has been melted (including partial melt) and vapor, as a function of the impact velocity and impact angle. Volumes are normalized to melt produced by vertical impact.

Scaling Laws for Melt Volumes: For impactor velocities greater than 8 km/s, scaling laws were obtained for the total volume of H_2O melted and vaporized during an impact event as a function of impact velocity U, target temperature T, angle of impact Θ, and impactor volume V_P.

$$V_{Vap} = V_P\left(1.0\times10^{-4}T + 0.07\right)U^{1.7}\sin^{0.6}(\Theta) \quad (1)$$

$$V_{Melt+Vapor} = V_P\left(2.8\times10^{-4}T + 0.4\right)U^{1.6}\sin^{0.7}(\Theta) \quad (2)$$

For impact velocities of 5-8 km/s the melt volume will deviate from this scaling law by about 50%. Below 5 km/s very little melt is produced for most starting temperatures.

The angle dependence follows a slightly different power law than shown in Pierazzo et al [7] for the same range of angles, $\sin^{0.8}(\Theta)$. However, this is not unexpected given the different pressure regime and target material. Angular dependences were not given in [8]; and interestingly, [9] suggest more melt results from shallower impacts, for icy bodies with a porous surface layer.

Melt Left in the Crater: The hot plug observed in crater formation simulations by [1] is composed almost entirely of partial melt. In Figure 3, we compare the volume of the hot plug with the volume of material shocked to, or above, the critical pressure for incipient melting, P_{IM}. Either very little of the shock melted material is lost from the crater or a non-negligible amount of material is heated to the melting point during crater collapse due to shear. To within the uncertainty of the numerical simulations, we suggest that a nearly equivalent volume of material that is shocked to the melting point can be found concentrated in the hot plug at the center of the impact crater.

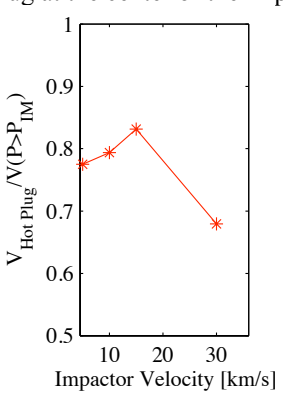

Figure 3. Volume of the hot plug normalized to volume of H_2O ice shocked above the pressure for incipient melt. Above impact velocities of 30 km/s very little partial melt is found in the collapsed crater [1].

Comparison to Previous Work: Pierazzo et al [10] determined scaling laws for the volume of H_2O ice that is completely melted during a vertical impact event using ANEOS parameters from Tonks [11]. More recent work [8] suggests significantly lower melt volumes are produced, however this was interpreted as being due to different initial temperatures (Figure 4). Our simulations suggest that significantly less melt is produced than [10] suggest. We find the discrepancy is not due to target temperature and we are not able to reproduce the results of [10] using the same EOS.

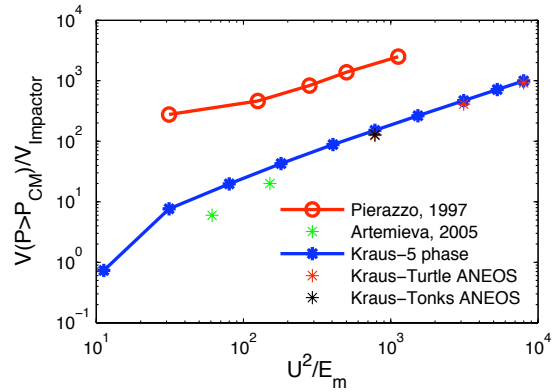

Figure 4. Comparison of scaled volume of ice reaching an entropy of 3.160 kJ/kg/K (completely melted at 1 bar) vs. scaled energy: Pierazzo 1997 [10] (red open circles and line), Artemieva 2005 [8] (green asterisks) for 93 K target temperature, 5-phase EOS (blue asterisks with line). For direct comparison, we calculated melt volumes for two sets of ANEOS parameters for H_2O (red and black stars; parameters from Turtle & Pierazzo 2001 [12], Tonks et al. [11]).

Conclusions: We have determined accurate scaling laws for the amount of H_2O ice that is melted or vaporized during an impact event as a function of impactor size, target temperature, impactor velocity, and impact angle. We show that a large fraction of the H_2O ice that has been at least partially melted is located in the hot plug at the center of the final crater.

References:

[1] Senft, L.E. and S.T. Stewart (2009) *40th Lunar and Planetary Science Conference*, abs #1444.
[2] McGlaun, J.M., S.L. Thompson, and M.G. Elrick (1990) *International Journal of Impact Engineering* **10**, 351-360.
[3] Senft, L.E. and S.T. Stewart (2008) *Meteoritics and Planetary Science* **43**(12), 1993-2013.
[4] Kraus, R.G. and S.T. Stewart, in prep for *Earth and Planetary Science letters*
[5] Ahrens, T.J. and J.D. O'Keefe (1972) *Moon* **4**, 214-249.
[6] Stewart, S.T., A. Seifter, and A.W. Obst (2008) *Geophysical Research Letters* **35**(23).
[7] Pierazzo, E. and H.J. Melosh (2000) *Icarus* **145**(1), 252-261.
[8] Artemieva, N. and J.I. Lunine (2005) *Icarus* **175**(2), 522-533.
[9] Artemieva, N. and J. Lunine (2003) *Icarus* **164**(2), 471-480.
[10] Pierazzo, E., A.M. Vickery, and H.J. Melosh (1997) *Icarus* **127**(2), 408-423.
[11] Tonks, W.B., E. Pierazzo, and H.J. Melosh (1997).
[12] Turtle, E.P. and E. Pierazzo (2001) *Science* **294**, 1326-1328.