Retention of water during planet-scale collisions.
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Introduction: Terrestrial planets are believed to collisionally accumulate through a final formation stage dominated by large impacts between Moon-to-Mars sized objects (*e.g.*, [1]). It has been suggested [2-3] that collisions between growing terrestrial planets and hydrous protoplanetary embryos that originated in the outer asteroid belt region represent an important source of water for Earth-like planets, and for the Earth in particular.

Morbidelli et al. [2] proposed a primary source of Earth's water was collisions with a few water-rich embryos with masses ~ 0.03 – 0.1$M_\oplus$ that originally formed in the 2.5 to 4 AU region with bulk water abundances similar to those of carbonaceous chondrites (up to ~ 10% by mass). Such objects could have been perturbed into orbits that cross the inner terrestrial region [2]. N-body simulations of late stage terrestrial accretion [2,4-7] have aimed to quantify the amount of water delivered to final planets through such collisions as a function of disk and accompanying giant planet orbital parameters. These works have typically assumed 100% accretion efficiency. However, the specific impact energy of planet-scale impacts greatly exceeds the latent heat of vaporization of water ice, and the efficiency of water retention could have been substantially lower.

Our goal here is to investigate the retention of water during large scale impacts using direct hydrodynamic simulation.

Method: We utilize a smoothed-particle hydrodynamics (SPH) method [8-10] which incorporates an improved version [11-12] of the sophisticated equation of state ANEOS [13]. The SPH code is a variant of that by Benz (*e.g.* [14]) that employs a tree code to calculate explicit gravitational interactions, and variable smoothing lengths. Material strength is ignored, a valid assumption for the sizes of interest here. The energy budget is determined by shock dissipation, and compressional heating and expansional cooling work.

With ANEOS all thermodynamic quantities are derived from an interpolation function of the Helmholtz free energy, with density and temperature as independent variables. ANEOS offers a limited treatment of phase changes, and can handle mixed phase states (e.g., liquid-vapor) within a single SPH particle by assuming the phases are in temperature and pressure equilbrium and computing a mass fraction and pressure contribution from each phase.

A substantial upgrade to ANEOS has been completed by Melosh [11-12]. ANEOS is now equipped with an improved cold compression curve and with the ability to describe molecular gases. Figure 1 shows the P-S phase diagram for water using the new ANEOS and associated constants (red curves), which provides a good match to real H_2O for the important vaporization phase boundary (thick black curve) and critical point (CP on the graph; red and blue stars are the new and old ANEOS critical point, respectively).

Initial conditions: We consider collisions involving

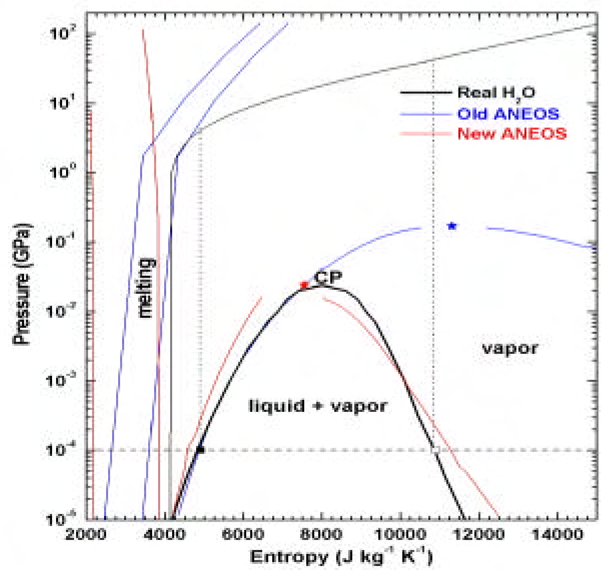

Figure 1: Phase diagram for H_2O.

a roughly Earth-mass differentiated protoplanet target containing 0.89$M_\oplus$ with 30% iron and 70% forsterite by mass, described by N=90,000 SPH particles and having an initial surface temperature ~ 2000 K (see [9] for details). As our default impactor, we consider the idealized case of a pure water ice object, containing 0.08$M_\oplus$, described by N = 20,000 particles, and having an initial surface temperature ~ 250K. Impacts are simulated for a variety of impact velocities relative to the pair's mutual escape velocity, $v_{esc} = \sqrt{2GM_T/(R_{imp}+R_{tar})}$ (≈ 8.5 km/sec for the objects modeled here), where M_T = 0.97$M_\oplus$ is the total colliding mass and R_{imp} and R_{tar} are the impactor and target radii. We consider a range of scaled impact parameters, b, where $b = \sin\xi$, and ξ is the angle between the surface normal and the impact trajectory so that b = 1 for a grazing impact. Each impact is tracked for approximately a day of simulated time.

Results: We have completed a survey of ~ 30 high-resolution (N_T = 110,000) simulations of impacts between planet-scale objects involving water ice as a primary constituent. Figure 2 shows the fraction of the system's water on unbound/escaping trajectories at the end of each simulation as a function of the impact velocity, v, scaled to v_{esc}, and the scaled impact parameter.

For random impact orientations, the most likely impact angle is 45º ($b \approx 0.7$), with 50% of all collisions occurring at angles between 30° and 60° ($0.5 \leq b \leq 0.87$). By contrast, the limiting head-on collision cases shown (with b = 0) would be extremely rare. Water losses are substantial over all impact velocities for $b \geq 0.5$, or for 75% of all collisions. By comparison, *e.g*., impacts with $(v/v_{esc}) \approx 1$, $b \approx 0.7$, $M_{imp}/M_T \sim 0.1$ and a terrestrial composition impactor (ice-free) yield only of order $0.005M_T$ (or ~ 5% of the impactor's mass) in escaping material [9].

Also shown (open squares) are results from two simulations involving $M_T = 0.96M_\oplus$ and a differentiated $0.05M_\oplus$ impactor containing 10% water ice, 63% forsterite, and 27% iron. The fraction of water lost is similar but somewhat higher, presumably because in these cases the water was initially located in the outer layers of the impactor that were more vulnerable to loss than its central regions.

Discussion: For the majority of collisions between an Earth-size target and a hydrous planet-scale impactor, water losses are substantial. The results here suggest that more than 50% of the impactor's water will be lost for collisions with impact velocities greater than $1.4v_{esc}$ and impact angles greater than 30° ($b \geq 0.5$). Lower velocity, more head-on impacts lead to higher retention rates.

The overall influence of these results on the ability of hydrous protoplanetary embryos to deliver water to growing terrestrial planets will be a strong function of the characteristic relative velocities between the inner planets and impactors originally formed exterior to ~ 2.5AU. For example, two simulations of Earth's accretion in [2,15] found that a partially grown "Earth" (containing ~ 0.63 to $0.71M_\oplus$ at the time of the impact) collided with a hydrous object containing ~ 0.05 $M_\oplus$ and an estimated ~ 10% water by mass with relative velocities before the impact of 5.5 and 8.8 km/sec. These would correspond to $(v_{imp}/v_{esc}) \approx 1.2$ and 1.4, for comparison with Fig. 2. More recent models [e.g., 4-7] may provide improved estimates.

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References: [1] Agnor, C. B., Canup, R. M., Levison H. F. (1999) *Icarus* 142, 219-237; [2] Morbidelli, A., Chambers, J., Lunine, J. I., Petit, J. M., Robert, F., Valsecchi, G. B., Cyr, K. E. (2000) *MAPS* 35,1309-1320; [3] Lunine, J. I, Chambers, J., Morbidelli, A., and Leshin, L. A. (2003) *Icarus* 165, 1-8; [4] Chambers, J. E. & P. Cassen (2003) *MAPS*, 37, 1523-1540. [5] Raymond, S. N., T. Quinn, & J. I. Lunine (2004), *Icarus* , 168, 1-17; [6] Raymond, S. N., T. Quinn, & J. I. Lunine (2005), *Icarus* , 177, 256-263; [7] Raymond, S. N., T. Quinn, & J. I. Lunine (2005), *Astrophys. J.* , 632, 670-676. [8] Canup, R.M. & Asphaug, E. (2001) *Nature* 412, 708-712; [9] Canup, R. M. (2004) *Icarus* 168, 433-456; [10] Canup, R. M. (2005) *Science* 307, 546-550; [11] Melosh, H. J. (2000) *LPSC XXXI*; [12] Melosh, H. J. (2005) *MAPS*, submitted; [13] Thompson, S.L. & Lauson, H.S. (1972) *Sandia Tech. Rep. SC-RR-710714*, [14] Benz, W., Cameron, A.G.W. & Melosh, H.J. (1989) *Icarus* 81, 113-131; [15] Morbidelli, A, personal communication.

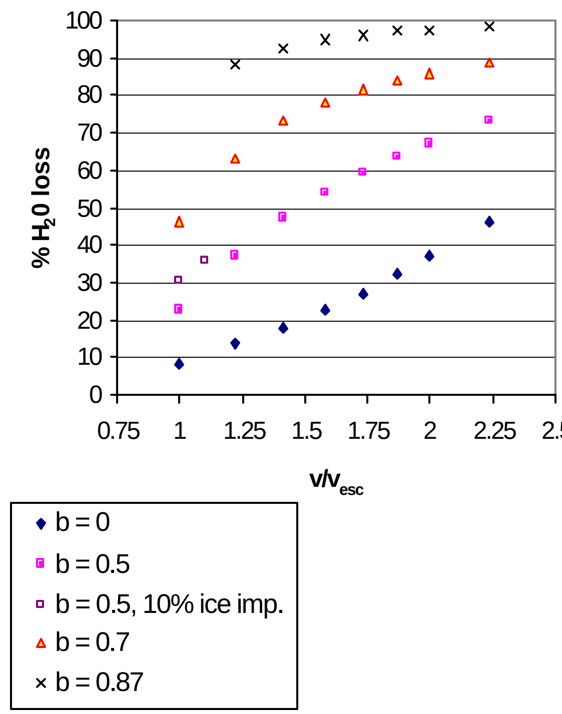

Figure 2: Results of SPH simulations involving ice-rich planet-scale impactors with ~ Earth mass targets. Most simulations involved a pure ice impactor, with 2 as indicated involving a 10% ice, 90% rock impactor.