MODELING MOON-FORMING IMPACTS: HIGH-RESOLUTION SPH AND CTH SIMULATIONS. R. M. Canup[1,2] and A. C. Barr[1,3] [1]Center for Lunar Origin and Evolution, Southwest Research Institute, 1050 Walnut St. Suite 300, Boulder, CO 80302 (robin@boulder.swri.edu); [2]Planetary Science Directorate, SwRI; [3]Department of Space Studies, SwRI.

Introduction: One of the key outstanding questions about the giant impact theory for the formation of the Moon is whether the Moon is ultimately derived from material that originated in the protoearth's mantle or from the impactor's mantle. This issue is critical to interpreting various compositional relationships between the Earth and Moon. Prior hydrodynamical simulations [1-3] find that successful impacts create a protolunar disk composed primarily of material that originated in the impactor, and yet the lunar and terrestrial oxygen compositions are identical [4]. Reconciling these results appears to require that the disk isotopically equilibrated with the protoearth soon after the impact [5], a potentially restrictive condition [6].

However to date, nearly all giant impact simulations have used a single approach: smooth particle hydrodynamics (SPH [7]), a Lagrangian method in which the impactor and protoearth are described by up to ~10^5 overlapping 3D particles. An alternative is an Eulerian, grid-based approach [8]. Recently Wada *et al.* [9] performed several simulations with a 3D Eulerian code and found broadly similar protolunar disk masses to those obtained with SPH. However, their simulations used a simplified equation of state and did not track whether disk material originated from the target or the impactor. Here, we report on the first detailed comparisons between giant impact simulations conducted with SPH and the Eulerian hydrocode CTH [10]. Our goal is to determine the effects of resolution and simulation method on impact outcome, in particular on the prediction that the protolunar disk is comprised primarily of impactor-derived material.

P-SPH. We use a new parallelized version of SPH that allows for an order-of-magnitude more particles than recent simulations [2,3]. In a 10^6-particle run, mantle particles have masses ~ 5×10^{21} g, corresponding to initial smoothing lengths ~ 130 km (vs. ~ 300 km 10^5-particle runs [2-3]). Smoothing lengths increase as local density decreases, so that diffuse regions are much more coarsely resolved. Our code [2,3] implements an improved version [11] of the equation of state ANEOS [12] that incorporates molecular vapor species. The code is a descendant of that of Benz (*e.g.* [7]), which employs a tree code to calculate explicit gravitational interactions. Material strength is ignored, a valid assumption for the planet-scale impacts simulated here. The energy budget is determined by shock dissipation [13], and work done by compressional heating and expansional cooling.

CTH. We also model moon-forming impacts using CTH [10], a well-known code widely used to model smaller-scale planetary impacts (e.g., [14]). We use CTH version 8.1 with self-gravity and ANEOS [12]. We have updated ANEOS in CTH per [11] , so that the equation of state is the same as that in our SPH simulations. The simulation shown here is being performed in a 3D Cartesian domain (30x30x6)$R_\oplus$, composed of 625x625x125 cubical elements, 320 km on a side, sufficient to resolve the protoearth with ~7500 elements (equivalent to 20 cells per projectile radius). Material is permitted to flow out of, but not back into, edges of the domain. We also use CTH to track the behavior of impactor vs. protoearth material.

Results. Fig. 1 (next page) shows results from 3 simulations (2 SPH, 1 CTH) of an impact in which the total mass is $M_T=1.02M_\oplus$, the impactor-to-total mass ratio is 0.13, the impact speed is equal to the mutual escape velocity, and the angular momentum is $1.25L_{EM}$ ($L_{EM} \equiv 3.5 \times 10^{41}$ g-cm^2/sec, the Earth-Moon system angular momentum). Broadly similar features are seen in all 3 runs for the first several hours of simulated time.

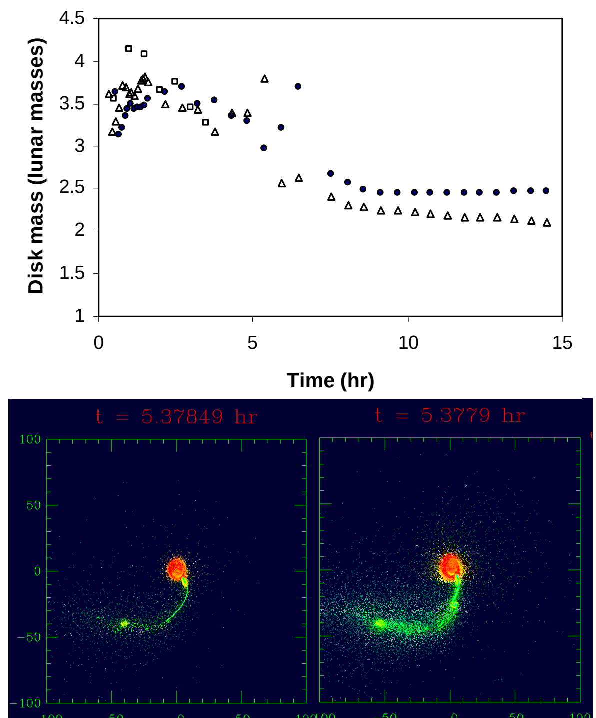

Fig. 2: (top) Orbiting disk mass vs. time in the 10^5 (triangles) and 10^6 (filled circles) particle SPH simulations, and CTH simulation (squares). (bottom) Frames at t = 5.4 hr from the N~10^5 (left) and N~10^6 (right) SPH runs.

Fig. 2 (top) shows the predicted disk mass vs. time from the 3 simulations. The primary difference in the two SPH simulations during the first 15 hours occurs at t ~ 5 hr (Fig. 2, bottom). At this point in the N~10^5 simulation, the inner portion of the extended arm of impactor material (composed primarily of the impactor's core) gravitationally self-contracts into a single object that re-impacts the protoearth. In the N~10^6 run, this material contracts into two clumps, and only the inner clump collides with the protoearth, leaving the 10^6 particle simulation with somewhat more mass in orbit. At t=15 hrs, the disk mass in the N~10^6 (N~10^5) case is 2.45 (2.12) lunar masses (about a 20% difference), with the disk comprised of 78% (82%) impactor-derived material, and containing 4% (3%) iron by mass. The faster drop-off in the disk mass with time for the N~10^5 run in the 7 to 15 hr period than for the N~ 10^6 case is likely a result of more rapid spurious disk spreading in the N~10^5 case due to its larger disk particle smoothing lengths [2]. In the first several hours of the CTH run, comparable disk masses to the SPH runs result. At t = 3.5 hr, the CTH run predicts that the orbiting mass is comprised of 84% impactor-derived material.

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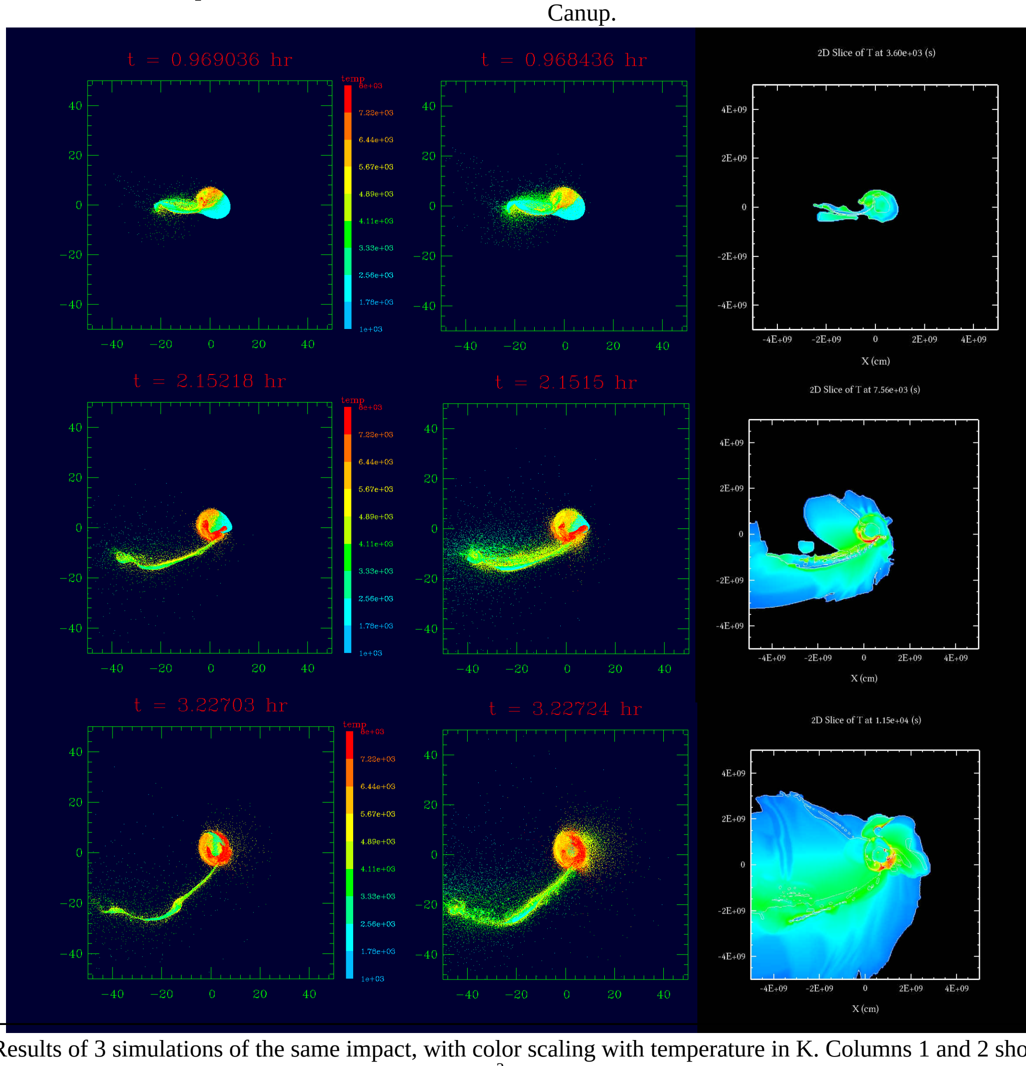

Fig. 1: Results of 3 simulations of the same impact, with color scaling with temperature in K. Columns 1 and 2 show 10^5 and 10^6 particle SPH simulations (distance shown in units of 10^3 km), while column 3 shows CTH results at comparable times.