GIANT IMPACT THEORY FOR ORIGIN OF THE MOON: HIGH RESOLUTION CTH SIMULATIONS.

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Introduction: In 1988, the CTH shock physics hydrocode was used to study the formation of the Moon by the impact of a Mars-sized body on the Earth (Fig. 1) [1]. For that simulation, CTH was augmented with a central radial gravitational body force which proved adequate for the relatively short duration of the simulation. More recently, simulations by Canup et al. [2], Canup [3] and Wada et al. [4] have used hydrocodes equipped with self-gravitational force integrators to follow the re-accretion of material after the impact. Canup et al. used an SPH method with an N-Body gravitational interaction whereas Wada et al. used an Eulerian grid formulation with a Fast Fourier convolution method for the gravitational interaction. Both methods have strengths and weaknesses for simulating the Moon formation problem. CTH, with its Eulerian formulation [5], adaptive mesh refinement [6] and a self-gravitational interaction model [7], can capitalize on the strengths of each method and be an excellent tool for looking at the Moon formation problem.

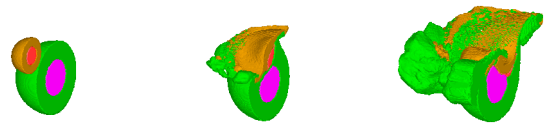


Fig. 1. Simulation of giant impact Moon formation hyopthesis using CTH in 1988[1]. The calculation covered about an hour of the event.

Self Gravity in CTH: Recent releases of CTH have included a parallel tree-based N-Body force solver [7] based on the method published by Barnes and Hut [8] to solve the self-gravitational interaction problem. So equipped, CTH has been used to investigate the formation of the South-Pole-Aitken Basin [9] where self gravity plays a significant role in the pattern of material failure and crater collapse.

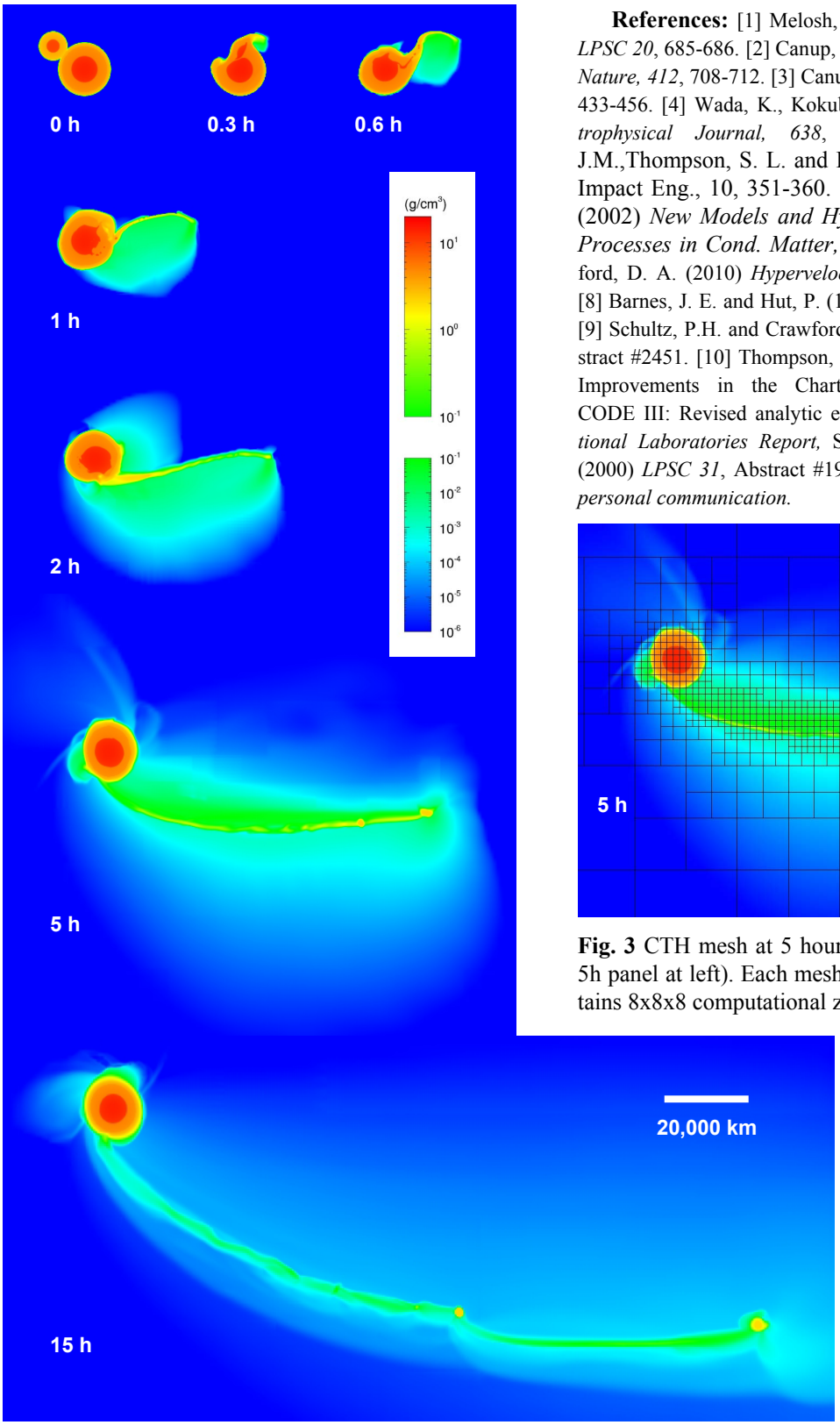
Parallelization of the Barnes-Hut method was accomplished within CTH by calculating a local Barnes-Hut tree on each processor, distributing a portion of each tree to all other processors depending on the physical distance to each processor's domain and calculating the N-body forces using the traditional Barnes-Hut criteria. With careful interleaving of calculations and message-passing, it can be shown that time and memory requirements scale well with processor count. Options are provided to allow mass-lumping of adjacent cells (typically 3x3x3) and super-cycling of the self-gravity calculation.

ANEOS Treatment of Molecules: The Analytical Equation of State (ANEOS) as originally written by Thompson [10] approximated the gas phase as single atoms. Melosh modified ANEOS to allow recombination into diatomic and triatomic clusters [11], shown to be an important part of impact simulations involving silicates [3]. We have added Melosh's modifications to CTH's ANEOS treatment and will include these changes along with Melosh's characterization of SiO_2 [12] starting with the next CTH release (Version 9.1).

Giant Impact Simulation: Figures 2-3 show a simulation of lunar formation from a giant impact using CTH with the new capabilities of adaptive mesh refinement (AMR), self gravity and molecular clusters. The calculation is 3-D with adaptive gridding keyed to density. The highest resolution region of the calculation uses 195 km cubical zones wherever density is greater than 0.01 g/cc. Lower density regions have lower resolution: 390 km zones where density >1e-3 g/cc, 780 km for density >1e-4 g/cc, 1560 km for density >1e-5 g/cc and 3120 km zones elsewhere (Fig. 3). In this calculation, the finest mesh is comparable to that used by Melosh and Kipp [1] but the overall extent of the mesh (400,000 km) and simulation time (17+ hours) are each an order of magnitude larger.

The impact parameters are the same as those of the Melosh and Kipp simulation [1], a Mars-sized body, traveling 8 km/s obliquely impacts the proto-earth. We replaced the original ANEOS mantle material description with Melosh's SiO_2 description that includes diatomic and triatomic molecular clusters [12]. The core material of the impactor and proto-earth were represented by ANEOS iron. The thermal profile of the proto-earth was identical to the Melosh-Kipp simulation. The calculation used 128 processors for 36 hours.

This calculation shows many of the same features seen in calculations by Canup [3] and Wada et al. [4], including clumps, streamers and spiral shocks. The main feature is an extensive streamer along which clumps of solid/liquid form over the course of several hours. Not shown, but included in the simulation, is an ability to determine mixing ratios of impactor and proto-earth materials that make up orbiting debris and eventually end up in the Moon. Future work will run the simulation for longer periods and greater extents, study a range of impact parameters, determine the amount of debris that ends up in orbit and study the influence of material properties on the outcome.



References: [1] Melosh, H. J. and Kipp M. E. (1989) *LPSC 20*, 685-686. [2] Canup, R. M. and Asphaug, E. (2001) *Nature, 412*, 708-712. [3] Canup, R. M. (2004) *Icarus 168:2*, 433-456. [4] Wada, K., Kokubo, E., Makino, J. (2006) *Astrophysical Journal, 638*, 1180-1186. [5] McGlaun, J.M.,Thompson, S. L. and Elrick, M. G. (1990) Int. J. Impact Eng., 10, 351-360. [6] Crawford, D. A., *et al.* (2002) *New Models and Hydrocodes for Shock Wave Processes in Cond. Matter,* Edinburgh, U.K. [7] Crawford, D. A. (2010) *Hypervelocity Impact Symposium 2010*. [8] Barnes, J. E. and Hut, P. (1986) *Nature*, 324(4):446-449. [9] Schultz, P.H. and Crawford, D. A. (2008) *LPSC 39,* Abstract #2451. [10] Thompson, S.L. and Lauson, H.S. (1972) Improvements in the Chart D radiation-hydrodynamic CODE III: Revised analytic equations of state, *Sandia National Laboratories Report,* SC-RR-71. [11] Melosh, H.J. (2000) *LPSC 31*, Abstract #1903. [12] Melosh, H.J. (2009) *personal communication.*

Fig. 3 CTH mesh at 5 hours after impact (compare to 5h panel at left). Each mesh block outlined above contains 8x8x8 computational zones.

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Fig. 2. Giant impact simulation of a Mars-sized body striking the Earth with properties described in the text. Color represents log of density in the bilateral symmetry plane. The sequence represents 15 hours of simulation time. The first three panels at the top correspond to the times of the original Melosh and Kipp[1] calculation of Fig. 1.