SIMULATIONS OF MOON-FORMING IMPACTS. R. M. Canup[1], E. Asphaug[2], E. Pierazzo[3], and H. J. Melosh[3]; [1]Southwest Research Institute; 1050 Walnut Street, Suite 426; Boulder, CO 80302; robin@boulder.swri.edu; [2]Earth Sciences Department, University of California; Santa Cruz, CA 95064; asphaug@es.ucsc.edu; [3]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ.

Introduction: An impact between the early Earth and a roughly Mars-size protoplanet is believed responsible for the origin of the Moon [1, 2]. A potential Moon-forming impact must eject sufficient mass and angular momentum into bound orbit to form a lunar-mass moon beyond the Earth's Roche limit; the ejected material also must be depleted in iron. In the least restrictive scenario, the lunar-forming impact yields an Earth-Moon system with nearly its current mass and angular momentum (L_{EM}), so that no significant later dynamical modification of the system is required. A Moon forming event near the very end of Earth's accretion also avoids difficulties associated with potential iron contamination of the Moon subsequent to its formation, which could be a problem if the Moon formed earlier in the Earth's accretion (e.g, [3], [4])

Recent work [5] has found that an impactor containing roughly 0.1 Earth masses (M_E) colliding with a target protoearth of ~ $0.9M_E$ with an impact angular momentum ~ $L_{E\text{-}M}$ can produce a sufficiently massive and iron-depleted protolunar disk. However, that work utilized a simple equation of state, Tillotson [6], that lacks an actual treatment of phase changes and mixed phase states. Here we have incorporated a newly upgraded version [7] of the more sophisticated equation of state ANEOS into the smoothed-particle hydrodynamics (SPH) method utilized in [5]. Initial results are presented using this version of ANEOS, which includes an upgrade to allow for the formation of molecular vapor.

Method: The SPH code utilized here is a variant of that by Benz (*e.g.* [8]) that employs a tree code for gravitational interactions, and variable smoothing lengths. Internal strength of the objects is ignored, a valid assumption for the sizes of interest here. The energy budget is determined by shock heating, (*P dV*) work, and the equation of state; radiative transfer is not included.

ANEOS [9] is a semi analytical FORTRAN package created for use with a number of hydrocodes. Its advantage over much simpler and widely used analytical equations of state, like Tillotson, is that in ANEOS all the thermodynamic functions necessary to describe the equation of state are derived from the Helmholtz free energy, with density and temperature acting as independent variables. This approach assures thermodynamic consistency. Furthermore, unlike Tillotson, ANEOS offers a limited treatment of phase changes, and it can handle mixed phase states (e.g., liquid-vapor). This enables ANEOS to describe melting and vaporization, which is particularly important for the late stages of an impact after material has been released from the shock state. ANEOS' thermodynamic sophistication requires that the properties of a given material are provided in the form of an array of ~ 40 variables, some with direct physical meaning (e.g., reference density, pressure, temperature, Debye temperature, Grüneisen coefficient, melting temperature, heat of fusion, etc.), others used simply as interpolation parameters to insure a good fit to the real properties of the material as determined through experiment. Arrays containing the atomic number and the mass fraction of each element present in the material are also required.

Recently, a substantial improvement to ANEOS has been completed by Melosh [7]. The upgrade allows for a more realistic description of vapor phases and of the liquid-vapor phase boundary (including the critical point). ANEOS is now equipped with an improved cold compression curve and with the ability to describe molecular gases. To take advantage of the upgrade it is necessary to modify the available material ANEOS equations of state; currently, this has been done only for dunite and ice. The simulations here use an upgraded dunite equation of state, and the old iron equation of state.

Initial Conditions: We consider collisions between a target protoearth and impactor each with a two-component core-mantle structure. We create these objects by first simulating the head-on collision of an iron impactor into a dunite target; the mass of iron is set to approximate a terrestrial iron fraction. The end result is a self-differentiated and collisionally heated dunite/iron protoplanet.

Sample Result: Using initial objects generated in this manner, Figure 1 shows one of our preliminary simulations of a potential Moon-forming impact incorporating the upgraded ANEOS; the final frame is after 24 hrs of simulated time. Here the impactor-to-total mass ratio is $\gamma = 0.13$, impact angular momentum is $1.23L_{E\text{-}M}$, total colliding mass is 1.019 Earth masses, and the impact velocity was $1.02v_{esc}$ (where v_{esc} is the mutual escape velocity of the colliding objects). We note that because of material density differences when moving from Tillotson to ANEOS, a somewhat different γ value is required for a fixed impact angular momentum and impact parameter, as already observed in [10].

At the end of the simulation, we classify the particles as 1) escaping, 2) orbiting, or 3) contained within the protoplanet. Escaping particles are those with positive total energies (kinetic + potential). We classify a particle as being in bound orbit if its total energy is negative, and its angular momentum exceeds that of a circular Keplerian orbit at the surface of the protoplanet. We use an iterative analytic method similar to that used in [5, 11] to solve for the mass and radius of the resulting protoplanet in an attempt to maintain consistency of comparison across the different simulations.

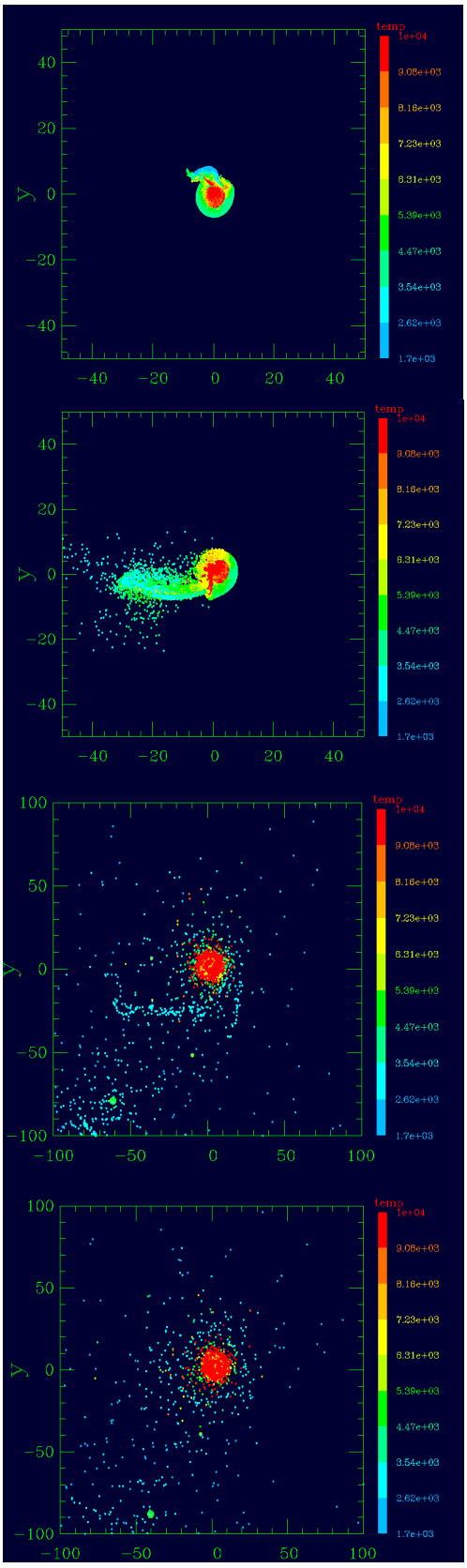

Figure 1: Four times (30 min, 2.5, 12 and 24 hrs) from an N = 30,000 particle simulation; color scales with temperature.

After 24 hrs, this simulation had 1.72 lunar masses (M_L) of material in bound orbit with $0.62M_L$ having equivalent circular orbits exterior to the Roche limit. The orbiting material contains 4% iron by mass, with 80% of the iron having equivalent circular orbits interior to the Roche limit. A mass of ~ $0.4M_L$ escapes and, accounting for the angular momentum carried away by the escaping material, the final system has an angular momentum of $1.16L_{E\text{-}M}$. The final mass of the Earth is $0.99M_E$, with a day of 4.6 hours.

Models of protolunar disk accretion [12, 13] find that a large moon forms at a characteristic distance of ~ $1.2a_{Roche}$, with a mass that is a function of the initial disk mass, M_D, and angular momentum, L_D:

$$M_M \approx 1.9L_D / \sqrt{GM_{\oplus}a_{Roche}} - 1.1M_D - 1.9M_{esc}$$

where M_{esc} is the amount of escaping material during accretion. Using $M_{esc} = 0$, the predicted moon mass resulting from the simulation shown here is $1.24M_L$.

Dependence on impact velocity: Recent simulations have assumed an impact velocity equal to v_{esc} [2,3,5]. This is the minimum impact velocity, but higher velocities could also be appropriate; the range of impact velocities capable of producing the Moon would provide information about the impactor's pre-impact orbit. For the same impact parameter, target, and impactor masses used in the simulation above, we have performed several simulations with varying impact velocities; results are shown in the table below. Velocities at infinity between 2 and 4 km/s would be appropriate, e.g., for an object with a=1 AU and eccentricity ~0.05–0.15. A study to assess the effect of v_{Inf} >0 on the mass and iron fraction of orbiting material is currently underway.

v_{imp}/v_{esc}	v_{Inf} (km/sec)	M_D/M_L	M_{Fe}/M_D	L_D/L_{EM}
1	0	1.0	0.05	0.18
1.02	1.9	1.7	0.04	0.30
1.05	3.0	1.9	0.08	0.34
1.10	4.3	1.8	0.09	0.35

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