A NUMERICAL STUDY OF THE GIANT IMPACT ORIGIN OF THE MOON: THE FIRST HALF HOUR. M.E. Kipp* and H.J. Melosh**, *Sandia National Laboratories, Albuquerque, NM 87185, **Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

Recent theoretical [1] and numerical [2,3] studies of the moon's origin have provided strong support for the "giant impact theory" originally proposed by Hartmann and Davis [4] and by Cameron and Ward [5]. Supported by Wetherill's [6] study of the terminal phases of planetary growth, this theory proposes that the moon originated when a Mars-size protoplanet in an orbit similar to the proto-earth's orbit collided with the proto-earth and ejected a mass of hot material that eventually condensed to form the moon. This scenario is in harmony with the general chemical similarity between the bulk moon and the earth's primitive mantle (present mantle plus crust), and also accounts for the striking volatile depletions and refractory enrichments inferred from the lunar rocks [7].

Benz *et al.* [3] studied the outcome of a collision between a Mars-size protoplanet and the proto-earth using an ingenious "smoothed particle" hydrodynamic code that allows them to economically compute the dynamical evolution of self-gravitating material in three dimensions. They showed that a very grazing impact might separate the mantle from the core of the projectile. The two separate masses travel together along elongate elliptical orbits until the gravitational attraction of the projectile's former core perturbs its former mantle's orbit into a more circular form while the core's orbit becomes correspondingly more elliptical. The former projectile core subsequently impacts the proto-earth while the former projectile mantle attains orbit. The window in impact parameter for this scenario to result in a moon seems to be rather narrow. Although one can argue that earth has only one moon, admitting consideration of unlikely events, this model does not appear to explain the moon's unique chemistry in a natural manner. Since the moon in this model originates almost exclusively from the projectile, the general resemblance of its chemistry to the earth's primitive mantle must be considered fortuitous. Furthermore, the volatile depletions and refractory enrichments are also difficult to understand, since the material that results in the moon in this model is at most melted. Diffusion rates of volatile species through magma are probably too low for even a totally molten moon to lose significant proportions of its original complement of volatile elements to space through its surface.

Although Benz *et al.*'s [3] numerical scheme allows full treatment of self gravity, its spatial resolution in the crucial contact region between the projectile and proto-earth during the early phases of the impact is relatively poor, since each discrete mass element is initially about 1,000 km in diameter. It is in this important region that oblique convergence of the surfaces of the projectile and proto-earth induces the process of "jetting" [1] which results in extra-high pressures, temperatures, and ejection velocity of material caught in the "vise" between the impacting projectile and target.

We have made a detailed numerical study of this early phase in the impact between a Mars-size projectile and the proto-earth using the two-dimensional hydrocode CSQ II at National Laboratories. We have included central gravity but not yet self-gravity, largely due to computer time limitations. We have chosen to study the problem in two dimensions because of the finer spatial resolution available in 2-D, although we have performed a number of coarser grid computations in 3-D using the Sandia hydrocode HULL. A 3-D version of CSQ is currently in the testing stage and further computations may employ this code. The computations we report on here were performed using a cell size of 250 km square, which seems to offer adequate spatial resolution for the effects of jetting to be accurately computed.

We model the equation of state of the earth's and projectile's mantle and core using the ANEOS equation of state package developed at Sandia [8]. The ANEOS algorithim is based on approximations to the Gibbs Free Energy of the material and so all derived quantities such as pressure, temperature, density, and internal energy are thermodynamically consistent, unlike the widely used Tillotson equation of state formulation. The equation of state library already contained an adequate treatment of liquid iron, but we had to develop a new set of input parameters to describe mantle material. The resulting equation of state includes the olivine-spinel high pressure phase change and is an excellent fit to the shock Hugoniot data of McQueen *et al.* [9]. The liquid-vapor phase boundary is also in excellent agreement with laboratory data. Since much of the vapor cloud ejected from the impact region lies on or near this phase boundary, it is important that the code treat it correctly.

The initial state of the earth was also a concern in our computations. Lacking detailed information on the earth's density and thermal state 4.6×10^9 years ago, we adjusted the proto-earth's initial density and internal energy to match those of the present earth. Since the model has central gravity, the earth is self-compressed and the static pressure through its mantle and core agree with those of the present earth.

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Four different combinations of impact velocity and impact parameter have been studied to date using this refined model. Two "low velocity" impacts with a velocity at infinite separation ($v_\infty = 0$) were computed at impact parameters of 1/2 an earth radius and 1 earth radius. Two "high-velocity" impacts ($v_\infty = 7.8$ km/sec) were also computed. Computations were run from the moment of impact to about 2000 seconds (33 minutes) after impact, at which time material began to leave the grid at a distance of 25,000 km from the earth's center.

All computations showed that a dense, hot plume of vapor (in some cases with a small admixture of liquid phase material that consensed at later times) was ejected from the interface between the projectile and the proto-earth. The total mass of the plume ranges from one to ten lunar masses in all cases computed. The plume contains a mixture of projectile and proto-earth material in roughly equal proportions, although projectile material tends to dominate the highest velocity part. The plume travels fastest for the two computations at impact parameter 1 earth radius, although substantial amounts of material are initially ejected at speeds greater than low-earth orbital velocity in all the computations. Ballistic extrapolations of the material in the plume show that although some of it (predominantly the projectile-material-dominated part) escapes the earth, most of it is gravitationally bound to the earth. Estimates of the material's perigee using these ballistic extrapolations show that little material would orbit the earth **if it were in either the liquid or solid state.** However, although most of the material in the plumes at 1800 seconds after impact is on the liquid-vapor phase boundary, the liquid fractions are less than 10%. Central temperatures in the plume are in the neighborhood of 5,500°K while pressures are 600 to 700 bar. Plume density at this time is nearly 1000kg/m^3. The plume must thus undergo considerable expansion before it is substantially condensed. A semi-analytic approximation [10] shows that this expansion results in the development of additional lateral expansion velocities in the neighborhood of 3 to 5 km/sec at distances of 5 to 7 earth radii. This additional "boost" injects on the order of one lunar mass into orbit (outside the roche limit) in our best-studied case of a "high velocity" impact at impact parameter 1/2. Although these semi-analytic extrapolations are useful, we are presently trying to extend the full numerical computaions to later times.

The results of our computations have been plotted on color film with color-coded contours for material, temperature, and density at time intervals of 50 seconds after the impact. These results will be shown at the conference.

All of our results to date agree in suggesting that the vapor plume ejected during the impact of a Mars-size body and the proto-earth 4.6×10^9 years ago could have injected on the order of a lunar mass into earth orbit. The higher velocity impacts appear to inject material into higher orbits than the lower velocity impacts. Similarly, the more oblique impacts, which eject higher velocity plumes, succeed in injecting material into higher orbits. Since the material that makes up the moon condenses *in vacuuo* from previously vaporized earth and projectile mantle material, volatile depletions and refractory enrichments are expected [11]. Furthermore, since the molecular weight of oxygen is less than that of silicon or metals, oxygen should be preferentially lost and the condensed material should be reduced in comparison to the starting material, in agreement with the moon's generally reduced condition.

This vapor-plume model thus appears to provide the most plausible model of the moon's origin. We have studied a range of models, all of which appear to succeed in orbiting roughly a lunar mass. This implies that the moon's origin may not be so unlikely as Benz *et al.* [3] suggest, given the occurence of an appropriately large impact.

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