THE ORIGIN OF THE MOON: 3D NUMERICAL SIMULATIONS OF A GIANT IMPACT;

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Since the Kona meeting on the origin of the Moon in 1984 (1) much discussion of the origin has focussed on the single impact hypothesis (2, 3, 4, 5).

We have carried out a series of 3D numerical simulations of such an impact using the so-called "Smoothed Particle Hydrodynamics (SPH)" method (6). In this method a mass element, which may be fluid or solid, is represented by a particle whose "wave function" is spread out over space; the particles overlap in space and the forces on them arise (in our case) from gravitation and from pressure gradients.

We simulated the events taking place between the collision of a projectile with the protoearth and the subsequent formation of a disk around the protoearth; the evolution of such a disk to form the Moon has been discussed by Ward and Cameron (7) and by Thompson and Stevenson (8). Different impact velocities, impact parameters, and initial internal energies were considered. Particular care was taken in the choice of the equation of state to model as accurately as possible the thermodynamics of the material during and after the collision.

The following assumptions had to be made to keep the problem tractable. We neglected material strength. This is a fairly common hypothesis in hypervelocity impacts and is certainly justified during the impact itself, but obviously wrong a short time after. We do not think, however, that this assumption affects our result for the following reasons. First, most of the simulations were started with molten planets. Second, even when starting with solid planets the material put into orbit became very hot and therefore molten. Taking material strength into account would only affect the way the protoearth recovers its spherical shape after the impact.

Radiative transfer and radiative energy losses were not included either. This is justified by a timescale argument. The typical timescale for the shock to heat the material is about half an hour, whereas the timescale to transport the heat or to lose it by radiation is much longer. The resolution in the code is equivalent to a chunk of material of about 10^{24} grams, so the time needed to cool such a piece of rock greatly exceeds half an hour.

The equation of state we used is the Tillotson equation of state (9). This equation of state has 10 material dependent constants that are defined by fitting the analytical formula to experimental data. The main property of this equation is that for cold and condensed matter the equation allows for negative pressures which simulate tension, whereas for hot and expanded matter the equation goes asymptotically toward the equation of state for perfect gases.

In a first series of simulations (5) we assumed for convenience that both the protoearth and the impactor were made of granite, since the Tillotson equation of state for this material was available. The threshold velocity needed to vaporize common mantle rocks is usually smaller than that for granite, so this assumption is a conservative one. Calculations of new models are now in progress in which we have included iron cores in the protoearth and in the impactor.

We first ran a set of simulations involving 2048 particles assuming a mass ratio between the protoearth and the impactor of 10 to 1 and with both planets assumed to be made only of granite (without an iron core). It turned out that the successful simulations, that is, those leading to the formation of a disk of more than 2 lunar masses and with an angular momentum comparable to the present Earth-Moon system, are characterized by the following initial conditions. The relative velocity at infinity should be less than 4 km/sec; consequently the impact parameter must be large (roughly, the path followed by the center of the impactor should graze the protoearth's surface if that surface was not displaced by the collision). Starting with molten or solid planets does not seem to make a significant difference. The typical history of such a successful collision is as follows.

After the collision, in which the impactor is totally disrupted, parts of it move beyond the Roche lobe and are drawn back together in orbit due to self-gravity. The material forming this clump originated in that part of the impactor situated farthest away from the center of the protoearth during the collision. The clump moves on a very eccentric orbit that brings it back inside the protoearth's Roche limit; it does not, however, collide with the protoearth again, since during the first impact pressure gradients were strong enough to push the clump away from its initial ballistic trajectory, and tidal interaction with the distorted protoearth transferred additional angular momentum. Nevertheless, the clump is destroyed once again and spreads out to form a disk. The material in this disk almost exclusively originates from the impactor. The angular momentum of the system (protoearth-disk) ranges between 80–99% of the present Earth-Moon system, since the escape of some of the particles carries away some of the initial angular momentum of the impact. This somewhat low value of the angular momentum suggests that a more massive impactor should be considered. (Increasing relative velocity does not work!)

The simulations that did not lead to a disk were started with either a relative velocity at infinity larger than 4 km/sec or with too large an impact parameter. The first situation leads to a complete destruction of the impactor with the protoearth accreting most of the material and the rest being lost by the system, whereas the second situation leads to the almost total accretion by the protoearth of the impactor, the shock being too small to provide a sufficient boost for the ejected material not to collide with the protoearth again.

In the next set of simulations (involving 3008 particles) the mass ratio between the protoearth and the impactor was 7 to 3. We also assumed that both planets had an iron core. The mass fraction of the core for both planets was taken to be 0.31, which is the mass fraction of the present Earth's core. In these simulations, since the impactor was relatively massive, the impact parameter had to be small to insure a correct amount of angular momentum. It turns out that a collision with just the angular momentum now in the Earth-Moon system is close to a head-on one (even assuming 0 km/sec relative velocity at infinity), and therefore the results were similar to those obtained with the same small impact parameter for the 10 to 1 mass ratio: complete destruction of the impactor and accretion by the protoearth of most of its material.

If one increases the impact parameter, the simulations again end with the formation of a disk around the protoearth; however, the amount of angular momentum in the system is then about 40% higher than that in the present Earth-Moon system. These simulations nevertheless present interesting features. Because of its relatively high density, the iron core of the impactor is never destroyed during the impact, but it becomes highly distorted and elongated, and after being slowed by the collision with the mantle in the protoearth the core follows a very eccentric orbit extending out to about 1.5 Earth radii. At the end of the first revolution this core strikes the core of the protoearth and is accreted and mixed with that core. The disk that is formed around the protoearth is therefore exclusively composed of mantle material, mostly but not entirely from the impactor, and consequently the disk is extremely depleted in iron.

We have thus found that a giant impact on the protoearth can indeed lead to the formation of a prelunar accretion disk. These simulations allow us to narrow the range of possible impacts. The impactor should have a mass of roughly a quarter the protoearth's mass, and the relative velocity between the two planets should be less than 4 km/sec at infinity. The iron core of the impactor is accreted by the protoearth, and the disk is extremely depleted in iron. These calculations therefore strongly support the idea that a single major impact can produce a disk of material around the protoearth with enough mass and a suitable composition such that subsequent disk evolution should lead to a body like the Moon beyond the Roche limit.

A further result of these simulations is that the transfer of orbital kinetic energy into protoplanet rotational kinetic energy is a very inefficient process. A giant impact is sometimes invoked to spin up the protoearth enough so that instabilities develop and eventually lead to fission. Only our collision simulations with small impact parameters produced a merged protoplanet with negligible orbiting disk. Durisen and Gingold (10) point out that to produce a dynamic rotational instability in the protoearth, it would have to be struck by a body of comparable mass at an impact parameter comparable to an Earth radius. The results of our simulations show that such a collision would directly produce an orbiting disk of substantial mass rather than leading to a merger followed by fission. If the impact parameter is small enough so that a disk is not formed, then the angular momentum imparted is also insufficient for fission.

We have made color movies of our impact simulations which have proven to be very useful in understanding the details of the collisions.

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