THE GIANT IMPACT PRODUCED A PRECIPITATED MOON. A. G. W. Cameron, Harvard-Smithsonian Center for Astrophysics.

The author's current simulations of Giant Impacts on the protoearth show the development of large hot rock vapor atmospheres. The Balbus-Hawley mechanism will pump mass and angular momentum outwards in the equatorial plane; upon cooling and expansion the rock vapor will condense refractory material beyond the Roche distance, where it is available for lunar formation.

During the last seven years the author, together with several colleagues, has carried out a series of numerical investigations of the Giant Impact theory for the origin of the Moon (1-4). These involved three-dimensional simulations of the impact and its aftermath using Smooth Particle Hydrodynamics (SPH), in which the matter in the system is divided into discrete particles whose motions and internal energies are determined as a result of the imposed initial conditions. Densities and pressures are determined from the combined overlaps of the particles, which have a bell-shaped density distribution characterized by a smoothing length. In the original series of runs all particle masses and smoothing lengths had the same values; the matter in the colliding bodies consisted of initial iron cores and rock (dunite) mantles. Each of 41 runs used 3,008 particles, took several weeks of continuous computation, and gave fairly good representations of the ultimate state of the post-collision body or bodies but at best crude and qualitative information about individual particles in orbit.

During the last two years the author has been using an improved SPH program in which the masses and smoothing lengths of the particles are variable, and the intent of the current series of computations is to investigate the behavior of the matter exterior to the main parts of the body or bodies subsequent to the collisions. These runs are taking times comparable to a year of continuous computation in each case; they use 10,000 particles with 5,000 particles in the target and 5,000 in the impactor, and the particles thus have variable masses and smoothing lengths (the latter are dynamically adjusted so that a particle typically overlaps a few tens of its neighbors). Since the matter in the impactor provides the majority of the mass left in orbit after the collision, and since the masses of the particles that originated in the impactor are smaller than those in the target, the mass resolution in the exterior parts of the problem is greatly improved and the exterior particles properly simulate atmospheres in hydrostatic equilibrium.

So far three runs have completed calculations; these have target to impactor mass ratios of 5:5 (reported at the 1992 LPSC (5)), 6:4, and 7:3. Six additional runs are currently under way; these all have mass ratios of 8:2 and a variety of collisional angular momenta ranging from 1.2 to 2.2 times the present angular momentum of the Earth-Moon system. Most of these runs have progressed enough to support the conclusions about the calculations discussed below.

I have taken the initial temperatures of all colliding bodies to be 2,000 K, which is high enough realistically to represent a history of collisional accumulation and low enough to suppress thermal evaporation of matter from the surface. In the Giant Impact and in the subsequent fallout of most of the material from the impactor into the protoearth, a significant part of the surface region of the protoearth, typically about a hemisphere, is heated to about 14,000 K or more. If the colliding masses are nearly equal the heating is more evenly spread throughout the merged body, whereas if the impactor is a lot smaller than the target, the heating is more concentrated toward the surface which thus tends to be hotter than in the former cases. Wherever this hot rock appears in a surface region, rock vapor evaporates and forms a hydrostatic atmosphere around the body. This rock vapor is simply the vapor phase of the dunite equation of state developed by Jay Melosh (3); future studies will need to treat the chemistry more realistically.

I show in the figure the radial distribution of the temperatures of the particles in the mass ratio 7:3 case; the iron particles are shown in black and the rock particles in gray. Out to 4 earth radii the rock vapor is at 4,000 K or higher, which means that it has a substantial electrical conductivity. The angular velocity of these rock vapor particles decreases outwards from near the condensed surface, and the corresponding specific angular momentum initially increases but then also steadily falls off with increasing radius.

In all cases, the fallout from the impactor after the collision initially puts most of the iron core of the impactor and a significant part of its mantle into a single hemisphere of the target, initially producing a rotating elongated mass distribution. This is very effective in transferring angular momentum to the remaining external orbiting particles. Thus, as the infallen material settles toward a rotationally symmetric distribution, the external material is generally torqued to larger radial distances away from the central body, leaving the material within the first few earth radii consisting almost entirely of the evaporated rock vapor.

The rest of the story is an inference since the relevant physical processes are not included in the code. Within the last two years there has been a remarkable series of papers by S. A. Balbus and J. F. Hawley (6) which demonstrate that there is a powerful instability in a differentially rotating conducting fluid with a seed vertical component of the magnetic field; this leads to a rapid outward flow of angular momentum as long as differential rotation persists. The operation of this instability in the high temperature rock vapor atmosphere (which will inevitably be threaded by a magnetic field) will therefore transport angular momentum outwards from the condensed part of the mantle to produce rapid rotation within the atmosphere out to the Kepler point (at which the material goes into orbit about the central body). For a Giant Impact that produces a protosphere with about a 4 hour rotational period, the Kepler point lies close to the tidal Roche lobe at a little less than 3 earth radii. Beyond the Kepler point the Balbus-Hawley
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mechanism cannot shut down, and so it will continue to pump mass and angular momentum outwards in the equatorial plane, maintaining a small departure from rigid rotation below the Kepler point.

As the vapor flows away from the protoearth it progressively expands and cools and the most refractory components will condense from it, forming small planetesimals. The Balbus-Hawley mechanism will gradually become ineffective as the electrical conductivity decreases, but the remaining noncondensed vapor can probably undergo thermal escape from the protoearth, carrying away some of the angular momentum. The condensed materials, being beyond the Roche distance, are then free to accumulate into the Moon. The Moon thus formed would have a very refractory composition, but it will most probably accumulate some of the material from the impactor, that was left over from the Giant Impact and torqued to several earth radii, but which was never heated too strongly and thus contains less refractory material. The precipitation nature of this lunar formation scenario is reminiscent of some ideas of Ringwood (7).

According to these ideas, the angular momentum of the Earth-Moon system unexpectedly appears to be a remarkably significant quantity, being related to the approximate equality of the Kepler point and the Roche distance. This work was supported in part by NAGW-1598.