THE GIANT IMPACT OCCURRED DURING EARTH ACCRETION. A. G. W. Cameron, Harvard-Smithsonian Center for Astrophysics, and R. M. Canup, LASP, University of Colorado.

The earlier simulations by one of us (AGWC) of giant impact scenarios for the formation of the Moon [1–5] covered only a limited range of parameter space. With only a few exceptions, the mass of the impactor was confined to the range 0.1 to 0.2 Earth masses and the angular momentum in the collisions lay in the range 1–2 times that of the present Earth-Moon system (= 1 EMAM). The total mass of the colliding system was always taken to be one Earth. In general, a low angular momentum collision leads to a circumterrestrial disk of material in orbits mostly confined to within the Roche lobe, but somewhat extending beyond. A high angular momentum collision involves two collisions between the impactor and the target protoearth, as a result of which one or a few substantial bodies are usually left in stable orbits beyond the Roche lobe. These bodies are iron-free and nearly entirely remnants of the impactor derived from the hemisphere farthest from the protoearth during the second collision.

The general problem has been that for these parameters an impact with 1.0 to 1.25 EMAM has placed too little material in orbit to form the Moon. This range allows for a reasonable loss of angular momentum from the Earth-Moon system due to solar tides. To put enough mass in orbit to form the Moon has generally required of the order of 2 or more EMAM. For the simulations reported here, the mass ratio of protoearth to impactor has been taken to be 7:3 in order to increase the residual orbiting mass. Of greater importance is that the total mass of the system has been reduced below one Earth at the time of the giant impact for a majority of the simulations. Thus we deal with scenarios in which the giant impact occurred well before the end of Earth accumulation.

The simulations were carried out using smooth particle hydrodynamics (SPH); there were 5000 particles contained in each of the protoearth and the impactor, and the characteristic smoothing lengths of the particles adjusted themselves during the calculation to maintain mutual overlap with a few tens of their neighbors, in the manner described in [5]. In order to suppress particle evaporation, the initial temperature in the protoearth and in the impactor was set at 1000 K; this is a conservative procedure that makes sure that substantial amounts of energy must be imparted in a collision before an evaporation can take place. The impactor and the protoearth each contained 31 percent iron in the core and the remainder of the mass was in the form of dunite in the mantle. The ANEOS equation of state was used as described in [3]. The impactor and the protoearth were assumed to be at mutual rest at infinity. Previous studies in this series have shown that a positive velocity at infinity does not change the general character of the collisions, although it is likely to prevent a capture in the case where the impactor just misses the target.

The present series of simulations involved total masses at the time of giant impact varying from 0.5 to 1.0 Earths. For the 7:3 mass ratio that meant that the preimpact Earth mass varied from 0.35 to 0.7 Earths. The results are presented in Table 1. The meaning of the columns is as follows: Tmass is the total mass in the impact, in (present) Earth masses. Angmom is the angular momentum in the collision, in units of the present angular momentum of the Earth-Moon system (3.5×10^{41} cgs). Allowing for some loss of angular momentum to solar tides (which transfers it to the Earth-Moon orbit about the Sun), this should be in the range 1.00 to 1.25. The next six columns deal with the amount of mass left in orbit (i.e., with perigees greater than 1 protoearth radius) following the impact; these masses are all in units of the (present) Moon mass. Total is the sum of all such masses. In the next two columns <Roche means that the perigee is less than the Roche distance (taken as 2.89 protoearth radii, scaled as the cube root of the model Earth mass), and >Roche means that the perigee is above this distance, so that such mass is in principle free to clump into stable bodies. Escape means that the mass is on a hyperbolic orbit. In the subsequent two columns are given the distributions of mass of the orbiting debris, inside and outside of the Roche distance, if one uses the equivalent circular orbits of the particles instead of the perigees. These circular orbits are what would be obtained if material could be subjected to a dissipation (as by multiple collisions) with conservation of angular momentum but not energy; in this sense the circular orbit gives a more average position of the particle and thus is probably a better indicator of when mass is free to clump beyond the Roche distance. In fact, when there is a lot of mass in orbit beyond the Roche distance, fairly massive clumps are commonly formed, sometimes primarily one clump, sometimes several. This clumping has been ignored for the purpose of reporting the orbiting mass distributions.

For the cases of 0.5 and 1.0 total Earth masses at impact, an extended range of angular momenta were investigated, in order to see the general trends. It is quite clear that progressively higher amounts of mass are

Table 1. Results of giant impact simulations with different total masses involved and different angular momenta but protoearth/impactor mass ratios of 7:3. Multiply the total mass by 0.7 to get the mass of the preimpact protoearth and by 0.3 to get the mass of the impactor. The Roche distance is 2.89 protoearth postimpact radii. The equivalent circular orbit is the circular orbit having the same angular momentum as the immediate postcollision orbit of a particle.

Total mass (Earth)	Collision angmom (EMsys)	Mass outside protoearth in lunar units					
		total	perigee <Roche	perigee >Roche	escape	equiv. circular orbit <Roche	equiv. circular orbit >Roche
0.50	0.500	0.568	0.199	0.083	0.285	0.063	0.219
0.50	0.625	0.644	0.264	0.314	0.066	0.104	0.474
0.50	0.750	1.211	0.361	0.839	0.011	0.096	1.104
0.50	0.813	1.472	0.640	0.795	0.037	0.140	1.295
0.50	0.875	1.745	0.639	1.030	0.076	0.181	1.448
0.50	0.938	1.862	0.577	0.913	0.372	0.072	1.418
0.60	1.00	1.361	0.475	0.876	0.009	0.104	1.247
0.60	1.25	2.351	0.992	0.890	0.469	0.273	1.608
0.70	1.00	0.926	0.184	0.327	0.414	0.121	0.391
0.70	1.25	2.035	1.097	0.864	0.074	0.420	1.541
0.80	0.80	0.224	0.038	0.013	0.173	0.038	0.013
0.80	1.00	0.679	0.299	0.133	0.247	0.061	0.371
1.00	1.00	0.488	0.106	0.005	0.377	0.091	0.020
1.00	1.25	0.438	0.073	0.024	0.340	0.057	0.041
1.00	1.50	0.753	0.176	0.286	0.291	0.093	0.369
1.00	1.75	1.155	0.485	0.078	0.592	0.286	0.277
1.00	2.00	1.602	0.830	0.696	0.076	0.325	1.200
1.00	2.25	2.079	0.633	1.376	0.070	0.267	1.742
1.00	2.50	2.534	0.833	1.651	0.050	0.143	2.341
1.00	2.75	3.432	1.461	1.908	0.063	0.332	3.037
1.00	3.00	5.233	2.178	1.427	1.628	0.405	3.200
1.00	3.25	5.163	1.358	1.158	2.647	0.195	2.321

placed into some kind of orbit with increasing amounts of angular momentum. Some of this mass is clumped into bodies of significant size. The maximum yields of orbiting mass occur when the angular momentum in the collision is nearly enough to cause the impactor to miss the protoearth entirely (such a miss happens at 1.0 angular momentum units for the 0.5 Earth mass case and at 3.5 units for the 1.0 Earth mass case).

It is clear that for the angular momentum interval 1.0 to 1.25 the maximum yield in bound orbits lies in the impact total mass range of 0.6 to 0.7 Earth masses, or roughly two-thirds of an Earth. For the chosen mass ratio of 7:3 this means that the Earth was slightly less than half assembled prior to the impact. In this mass range the amount of material available for assembly into the Moon is more than adequate. Postimpact accretion must add about 1/3 Earth mass to the Earth and very little to the Moon. The fact that the lunar collisions are very energetic for that size body may play an important role here, due to the lunar orbital velocity near the Earth which is roughly double the lunar escape velocity.

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