THE IMPACT PHASE OF TERRESTRIAL PLANET ACCRETION: IMPLICATIONS FOR LUNAR ORIGIN. C. B. Agnor[1,2], R. M. Canup[2], H. F. Levison[2], [1]Department of Physics, University of Colorado, Craig.Agnor@colorado.edu, [2]Department of Space Studies, Southwest Research Institute, 1050 Walnut Street, Suite 426, Boulder, CO 80302, robin@boulder.swri.edu, hal@gort.boulder.swri.edu.

Two decades of analytical modeling and numerical simulation have revealed three general stages in the terrestrial accretion process: an early stage which commences with dust grains in a gas-rich nebula and ends with the formation of km-sized "planetesimals"; an intermediate stage in which planetesimals experience runaway growth and form lunar-sized "planetary embryos" in approximately 10^5 – 10^6 years; and a final stage dominated by mutual gravitational perturbations between planetary embryos, resulting in large, stochastic impact events and the formation of the final terrestrial planets after about 10^8 years. The prediction of a final impact-dominated phase coincides nicely with observed features in our solar system that are believed to be the result of giant impact events, including most significantly the Earth/Moon system.

The intermediate stage of collisional growth of roughly lunar-sized embryos has been extensively studied using statistical methods (*e.g.* [1] – [5]). Recent work [5] has modeled the accretional evolution of initially km-sized bodies throughout the entire terrestrial region (0.5 to 1.5 AU). Results from this work suggest that a few tens of planetary embryos with masses > 10^{26} g (a lunar mass ≈ 7.35 x 10^{25} g) form after about a million years and contain nearly all of the total mass in the system.

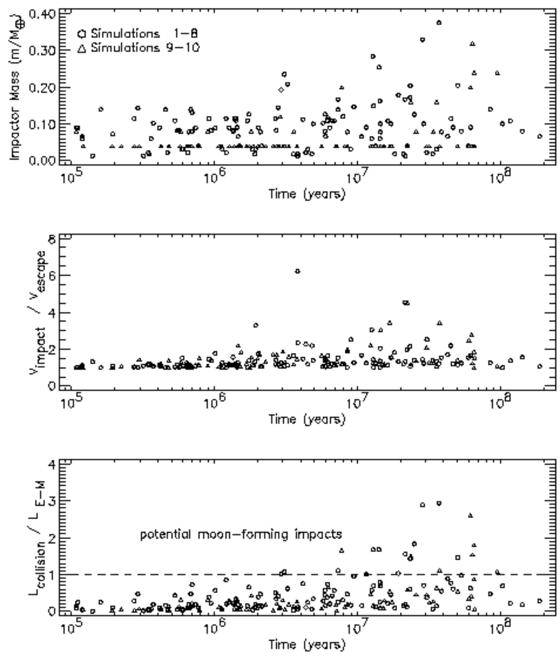
The final stage of terrestrial planet formation thus likely commences with a few tens of lunar-sized bodies on fairly circular orbits, which must then experience mutual perturbations and collisions to yield the final planets. Until recently, modeling of this stage had been limited to statistical methods, as the time scales involved (up to 100 million orbits) precluded simulations using direct N-body orbit integrations. Multiple works by Wetherill (*e.g.* [6] and [7]) using a Monte Carlo approach found, on average, about one impact between a body of nearly Earth-size and an impactor with at least a Mars mass per simulation. This generally agreed well with the type of impact that was believed to be required to yield the Earth/Moon system in the Giant-Impact scenario.

However, recent dynamical models of lunar formation in the giant impact scenario have raised new complicating issues. Works simulating lunar accretion from an impact-generated disk ([8] and [9]) suggest that an initial disk mass of at least 2 lunar masses is required to yield the Moon. Recent high-resolution SPH ("smoothed-particle hydrodynamics") simulations of impacts predict the formation of such massive disks for only two types of impacts (a) impacts with impact angular momenta > $2J_{\oplus\text{-M}}$, where $J_{\oplus\text{-M}}$ is the current angular momentum of the Earth/Moon system, or (b) "early-earth" impacts with $J_{imp} = J_{\oplus\text{-M}}$ that involve a total mass of about $0.65M_{\oplus}$ [10]. Thus impacts that have been shown to yield the Moon leave the Earth/Moon system either with a large excess of angular momentum or an Earth that must accrete ~35% of its mass after the moon-forming impact. Both scenarios suggest that the Earth/Moon system may have been significantly altered by later impacts, or that perhaps Earth had a retrograde spin prior to the lunar-forming event. The apparent difficulty in identifying a single impact that can simultaneously account for the masses and angular momentum of the Earth/Moon system has been one of the motivations for our study of the impact stage of planet formation [11]. In this study, we have emphasized the determination of not only typical impactor masses, but also impact angular momenta and the evolution of planetary spins during the final accretionary stage.

Direct integrations of the ~10^8-year impact stage are now feasible due to the development of new symplectic numerical methods, *e.g.* [11] and [12]. In our study, we have utilized a new algorithm, SyMBA, that allows for collisions and close encounters to be to be handled in a completely symplectic manner [13]. In a typical 2 x 10^8 -year simulation, this method conserves energy to about one part in 10^6. Figures 1-3 are composite plots of all impacts that occurred in 10 of our simulations. Eight of the simulations began with initial conditions taken directly from the output of the terrestrial zone calculation in [5] (22 initial embryos); two of the simulations began with 50 equal sized bodies. We assume complete mergers upon collision in all cases.

In general, we find similar impactor masses and timing as discussed in [6] and [7]. However here we are also able to examine impact angular momentum, and Figure 3 demonstrates that on average several impacts greater than or equal to the current angular momentum of the Earth/Moon system occur per simulation (mean number of impacts per simulation with $J_{imp} \geq J_{\oplus\text{-M}}$. is 1.6 for simulations 1-8, and 3.5 for simulations 9-10).

We also track the evolution of all of the planets' spins as they evolve due to impacts. We find that the final angular momenta of the earth-like planets (*i.e.* those with masses > 0.5 $M_{\oplus}$) are typically the combined result of several impacts which each make significant contributions. The average angular momentum delivered to an earth-like planet by the largest impactor ($\langle m_{lgst}\rangle = 0.30M_{final}$) is 1.44 $J_{\oplus\text{-M}}$; however, the second-largest impactor ($\langle m_{2nd\text{-}lgst}\rangle = 0.19M_{final}$) contributes an average of $0.67J_{\oplus\text{-M}}$. In addition, the average spin angular momentum of a planet immediately prior to experiencing a $J_{imp} \geq J_{\oplus\text{-M}}$ impact has an average value of 0.9 $J_{\oplus\text{-M}}$.



Figures 1-3: The impact angular momentum vs. time is shown for all impacts that occurred in 10 simulations of the final stages of terrestrial planet formation. The dashed line is the angular momentum of the Earth-Moon system.

The late-stage integrations performed in [11] and [12] make significant simplifying assumptions (*e.g.* merger upon collision), and more sophisticated models are clearly warranted. However, our results to date suggest that (a) the angular momentum of the Earth/Moon system could have resulted from more than one impact, (b) the moon-forming impact may not have been the last large impact on the Earth, and (c) the Earth may have been spinning rapidly prior to the moon-forming impact event. These findings reveal a larger range of parameter space that should be investigated by models of the impact-triggered formation of the Earth/Moon system.

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