Dynamical evolution of the Earth-Moon Progenitors.

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The origin of Earth's Moon has been a perplexing mystery for many decades. Lunar samples have been obtained indicating an age of the Moon to be roughly 60-120 Myr [1,2] younger than the Calcium Aluminum Inclusions in the chondritic meteorites. Updated measurements indicate an age difference of 70-110 Myr [3,4]. Additional information has been obtained for the composition of the Moon relative to the Earth, with surprising similarities and differences. However, the complete story of the formation of the Moon has yet to be told.

Simulations of a Moon-forming giant impact using smooth particle hydrodynamics have been successful in providing insight into what initial conditions are required with respect to the collision parameters and compositions [5]. But the mass of the impactor is largely unconstrained and can vary depending on the chosen model [6,7]. Using a dynamical 5 terrestrial planet model we present results that constrain some of this uncertainty and indicate a likely spatial origin of the proto-Moon if a mass ratio of 4:1 or 1:1 is assumed between the progenitors.

Method

We have developed a custom dynamical model (an improved version of [8]) in which the orbital parameters are determined seconds before a collision. We investigate a parameter space of initial semimajor axes and eccentricities of the proto-Moon. The initial conditions of the proto-Earth are determined through conservation of angular momentum with the current Earth-Moon system. All other orbital parameters for the other terrestrial and giant planets are taken from a recent common ephemeris. Mass ratios of 8:1, 4:1, and 1:1 are considered within a range of semimajor axis (0.76 – 1.55 AU) and eccentricity (0.0 – 0.1).

This model assumes a Solar System architecture of giant planets, however this may not have been the case for the era in question. Thus we investigate a Nice model [9] configuration for the 4:1 mass ratio to determine the possible consequences of the Nice model on early giant impacts.

Our simulations begin at a time where most material has been cleared from the early Solar System (~30 Myr after CAIs) and we evolve the system for 200 Myr or until a planet-planet collision occurs for each chosen initial condition. Completely inelastic collisions are assumed. We characterize each outcome based upon the collision time and resultant merged mass. A category of *success* describes a collision that occurs after 8 Myr and the colliding bodies are the proto-Moon and proto-Earth. A *pseudo-success* occurs after 8 Myr with a collision that produces an Earth-like mass but the colliding bodies are not the proto-Earth and proto-Moon. A collision after 8 Myr that doesn't produce an Earth-like mass is denoted as a *non-SS mass*. If the collision occurs before 8 Myr, the simulation is characterized by the *early* category and is not discriminant to the resultant merged mass. Cases where no collisions occur (stable) or a terrestrial body is ejected from the system are denoted as *NC* and *ejection*, respectively.

Results

We present the results of a high resolution set of simulations considering the 4:1 mass ratio within a Solar System like giant planet architecture (Figure 1). A total of 8110 initial conditions are considered to fully explore the parameter space which illustrates many interesting features.

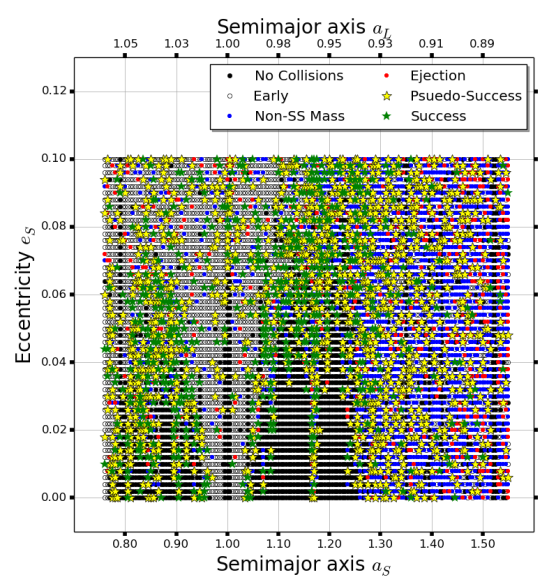

Figure 1: Evaluation of coplanar initial conditions for the Earth-Moon progenitors. The initial semimajor axis of the proto-Moon (S) and the proto-Earth (L) are indicated.

Local regions of *success* are evident in semimajor axis ranges of 0.80 – 1.00 AU and 1.08 – 1.30 AU where these regions have potentially different causes for *success*. The interior region is dominated by interactions between the proto-Moon and its terrestrial neighbors. The proto-Moon in the exterior region is influenced by interactions with its terrestrial neighbors and Jupiter. This is shown with a comparison of this map with the Nice model (Figure 2).

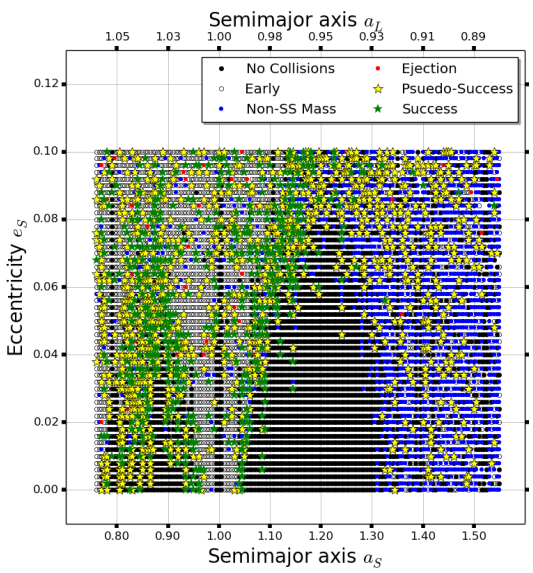

Figure 2: Same terrestrial planet initial conditions considering a 4:1 mass ratio except with a Nice model configuration of giant planets.

From comparison of these figures the interior (< 1 AU) region is almost identical while a more significant difference is seen at 1.165 AU. In this region there is a strip of *success* outcomes in the case of the Solar System that are induced by resonant interactions between the proto-Moon, proto-Earth, and Jupiter. At this location we have identified a possible mean motion resonance along with a secular perturbation from Jupiter that could affect the long term stability of the proto-Moon.

Much weaker features occur between 1.0 and 1.165 AU due to mean motion resonances in both the Solar System and Nice model architectures. Even though the 1.165 AU feature is not present in the Nice model simulations, both models demonstrate that the outcomes in the *success* and the *pseudo-success* categories are not uncommon. Overall there were slightly fewer collisions in the Nice model simulations where this is attributed different secular perturbations due to the assumption of nearly circular orbits of Jupiter and Saturn. In the model of the present Solar System, these eccentricities are approximately 0.05 leading to larger perturbations affecting the proto-Moon in the exterior (> 1 AU) region.

Discussion

Consideration of different initial conditions of a 5 terrestrial planet model have produced a wide variety of possible outcomes. However, not all these outcomes are equally probable. Due to the dominant gravitational interactions, some outcomes have a higher density localized within the parameter space. This is important in interpreting the likelihood of possible outcomes. Additionally, we have uncovered an interesting set of dynamics that would have occurred among the terrestrial planets through mean motion resonances. Most importantly, we provide estimates of the likely formation region of the proto-Moon.

Acknowledgements

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