MOON FORMATION FROM MULTIPLE LARGE IMPACTS. Robert I. Citron[1,2,3], Oded Aharonson[2], Hagai Perets[3], and Hidenori Genda[4], [1]Department of Earth and Planetary Science, University of California, Berkeley, CA 94720 (ricitron@berkeley.edu); [2]Department of Earth and Planetary Science, Weizmann Institute of Science, Rehovot, Israel 76100; [3]Department of Astrophysics, Israel Institute of Technology, Haifa, Israel 32000; [4]Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo, Japan 152-8551.

Introduction: Single giant impact models of Moon formation [1-3] are widely accepted because they explain the present angular momentum of the Earth–Moon system and the Moon's iron depletion. Similarities in isotope ratios (e.g., W and O) between the Earth and Moon can be explained by equilibration in the Earth–Moon system via a gas-rich protolunar disk [4, 5], or via impact dynamics if the evection resonance allows more initial angular momentum than currently observed [3]. Relaxing the initial angular momentum constraint allows for a smaller and faster impactor [3] or a collision between two bodies of similar size [2].

However, it is challenging to reconcile single giant impact parameters with the latest dynamical simulations of planetary formation. Recent n-body simulations [6, 7] show that impacts predicted by [1-3] are rare, particularly as the last giant impact to hit the proto-Earth. Combined with the isotropic distribution of impact angles [8-11], the probability of an impact with the necessary parameters to form the Earth–Moon system is only 2-8% [12, 13].

To reconcile impact dynamics with n-body results, we propose a multiple large impact model, in which the Moon formed from the merger of successive large impacts that each produced a distinct debris disk that spawned a small satellite. We test the hypothesis that smaller/faster impactors predicted in Earth's collisional history [6] would create small satellites that dynamically evolve and coalesce into a single final satellite.

Methods: We estimate the proto-Earth's collisional history using results from recent n-body simulations [6, 7]. We compute an average interval of ~16 Myr between embryo-embryo impacts of mass ratio $\gamma >$ 0.025 onto a proto-Earth with mass > 0.1 M_e (Earth mass), in addition to impact angle $\langle\theta\rangle \sim 45$ and speed relative to escape velocity $\langle v_{imp}/v_{esc}\rangle \sim 1.14$ [6]. Using the method from [12], we compute the average total mass of satellites formed over the proto-Earth's history to be 3.14 M_l (present Moon mass), with an average individual satellite mass of 0.38 M_l. This suggests that in a multiple-impact scenario, a lunar mass satellite can form even if two-thirds of the produced satellites are lost via ejection or re-accretion.

To determine the stability of multiple-satellite systems, we investigate the pre-impact interactions and the formation of debris disks in the presence of an existing satellite. We also examine impactors with lower mass and higher velocity, and plan to investigate the dynamics of multiple-satellite systems in future work.

Pre-Impact Interactions: Because the ~16 Myr interval between large impacts is much greater than the timescale of satellite formation (~1-100 yrs) and the timescale of satellite migration to $a_{sep} > 10$ R_e (tens of thousands of years), it is unlikely that subsequent impacts would greatly affect the dynamics of a proto-Earth–satellite binary. To confirm this, we simulated single-binary encounters using the direct n-body integrator Fewbody [14]. We examine encounters with a 0.4 M_l satellite orbiting the proto-Earth at distance a_{sep}=22 R_e (Earth radius), *i.e.,* the distance such a satellite would tidally migrate to in ~16 Myr. The impactor was given a mass of 1/40, 1/20, or 1/10 M_e, a velocity of 1 or 1.4 times the three-body critical impact velocity, and an impact parameter of 0 or 1 R_e for collisional trajectories, or 0.5, 1, or 10 a_{sep} for close encounters.

We find that almost all collisional trajectories for M_i=0.025 or 0.05 M_e result in a normal impact and the satellite remaining in orbit. As expected, the large a_{sep} and proto-Earth–satellite mass ratio result in preservation of the original binary during the collision. For a larger impactor, M_i=0.1 M_e, the satellite remains in orbit (with 6-12 times the initial a_{sep}) in 82-87% of interactions, and is otherwise ejected or re-accreted.

Impact Interactions: We conduct simulations of large collisions to determine if the presence of an existing satellite affects the formation of an impact-generated debris disks and to examine the disk mass and iron content for smaller and higher velocity impacts. Impact simulations are conducted using the Smoothed Particle Hydrodynamics (SPH) method [15] using the code described by [16].

To test the effect of a satellite on subsequent impact disk generation, we place a lunar mass satellite at 3, 5, 7.5, 10, 20, 40, or 60 R_e around a proto-Earth of mass 6.0×10^{24} kg that is impacted by a Mars-mass (6.0×10^{23} kg) planetary embryo at the two-body escape velocity. The planetary bodies are composed of a 3:7 core-mantle ratio using the Tillotson equation of state [17] parameters from [18]. Simulations used $N\sim10^5$ particles and progressed for at least 48-72 hours after impact, although the state of the system 24 hours after impact is used for computations to avoid errors from artificial viscosity introduced by large particle smoothing lengths present in the disk as it spreads. The mass of the post-impact disk was computed using a method similar to that in [3].

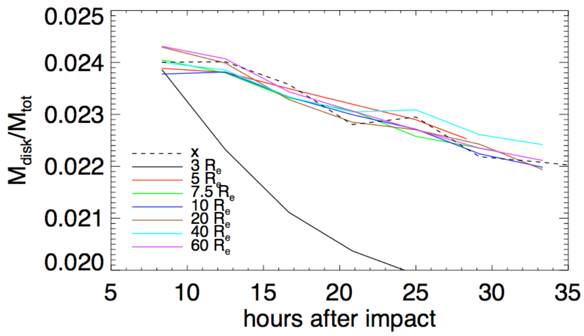

Figure 1. Disk mass versus time for a large impact with a prior satellite at various initial a_{sep}. The dashed line is a simulation without a prior satellite. Each line represents a mean for eight simulations at the specified orbital radius with the initial satellite starting a phase angles incremented at 45°.

We find that a pre-existing satellite with $a_{sep} > 5$ R_e has a negligible effect on the formation of an impact-generated debris disk (Fig. 1), with disk mass profiles that closely match that of a system without a pre-existing satellite.

We also examined disk mass and composition for impacts with $\gamma = 0.05$ and 0.025 and v_{imp}/v_{esc} between 1 and 1.4, impact parameters that are more common in n-body simulations of the final stages of terrestrial planetary formation. Results for these simulations (Fig. 2) show that while higher velocity impacts produce more debris, this is not always reflected in an increase in bound disk mass. Although iron concentration in the disk increases at higher impact velocities, if the higher iron concentration is primarily in the inner disk it may have less of an effect on the satellite's composition.

Discussion and Future Work: This work constitutes a preliminary examination of the feasibility of Moon formation via multiple large impacts. Such a formation scenario allows the Moon to form naturally as a cumulative result of typical impacts experienced by the proto-Earth, instead of a single chance giant impact. Considering the rapid migration of pre-existing satellites between subsequent impacts, we show that the dynamics of the proto-Earth–satellite binary and the process of impact-generated disk formation are largely unaffected by subsequent low-mass collisions. Additional work in progress will examine the dynamics of multiple satellite proto-Earth systems to determine the likelihood of forming a single large moon from multiple small satellites, and has so far shown that mergers in multiple satellite systems are possible. Even if the Moon formed from a single impact (no subsequent mergers), further study of multiple satellite systems is necessary because the proto-Earth likely formed several other satellites during its accretion.

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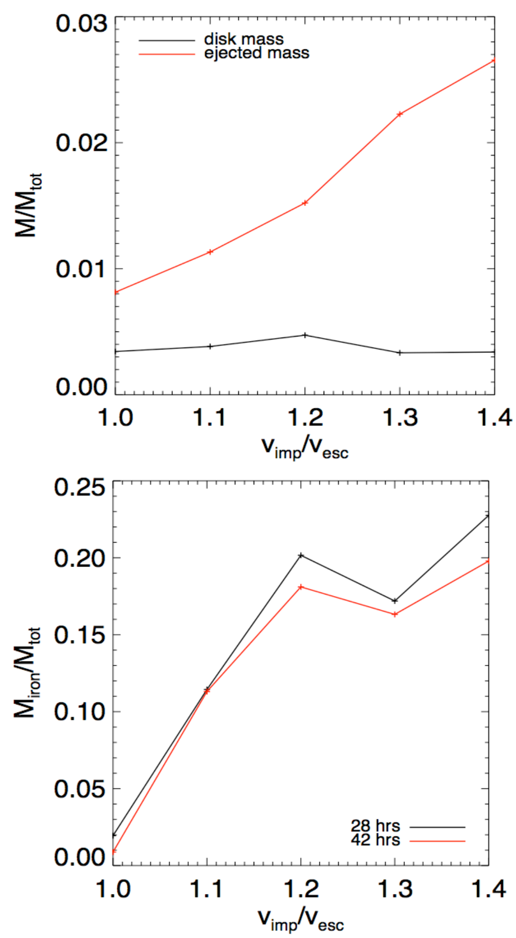

Figure 2. (top) Dependence on disk mass (black line) and ejected mass (red line) on impact velocity for impacts with $\gamma = 0.05$. Simulation uses N = 105 particles. (bottom) Dependence of disk iron concentration on impact velocity for a $\gamma = 0.05$ impact with $N = 10^5$ particles.