DISK ACCRETION EFFICIENCY IN A MULTIPLE-IMPACT LUNAR ORIGIN SCENARIO. J. J. Salmon[1] and R. C. Canup[1], [1]Southwest Research Institute Planetary Science Directorate, 1050 Walnut Street - Suite 300, Boulder, CO, 80302, USA (julien@boulder.swri.edu).

Introduction: The origin of Earth's Moon remains uncertain. The leading hypothesis involves an impact on Earth toward the end of its formation [1]. Depending on flavors of this general scenario, the size of the impactor could be similar to Mars or as large as half the Earth [2, 3, 4]. The impact creates a disk around the Earth, from which the Moon accretes. In previous works we explored the accretion of the Moon from disks in the context of the "canonical" impact [5] and "non-canonical" impact [6]. In those scenarios, the mass of the protolunar disks that were considered were 1.75-3 Lunar masses (M_L). Recently, [7] proposed an alternative scenario in which the Moon forms progressively via multiple smaller impacts. Each impact results in the formation of a "moonlet", and the Moon results from the consecutive merging of several moonlets. The masses of the disks that are produced in this context are much smaller than considered in previous works, of order 0.1-1M_L.

To estimate the mass of the moonlet formed from such disks, Rufu et al. used a standard analytical prescription [8] that gives an estimate of the mass of the moon formed from a given disk as a function of its specific angular momentum $J_{spec} = \frac{L_{disk}}{M_{disk}\sqrt{GM_{\oplus}a_R}}$, where L_{disk} and M_{disk} are the disk's angular momentum and mass, G is the gravitational constant, and $a_R \sim 2.9R_{\oplus}$ is the Roche limit for Lunar material density. In [5] we revised this expression using a more accurate numerical modeling of the protolunar disk, and found that the mass of the moon that would form from a given disk would be generally much smaller than predicted by [8], especially at large specific angular momentum $\left(J_{spec} \geq 1\right)$. Because the evolution of a < 1M_L disk has not been studied in detail, it is not clear if predictions from [8] or [5] would be accurate in this context. The initial mass and position of each "moonlet" are essential parameters for their subsequent tidal evolution and for whether moonlets formed by subsequent impacts will merge to grow the Moon. It has also implications for the number of moonlets, and thus the total number of impacts, that may be required to grow a lunar-mass object, which may affect the probability of success in this scenario.

Numerical model: We model the disk's evolution using a hybrid numerical model [5,9,10]. The code represents material within the Roche limit as a uniform surface density disk whose mass and outer edge position evolve with time due to viscosity and interactions with outer moons. Material beyond a_R is described by an *N*-body accretion simulation. The inner disk spreads viscously with either a radiation-limited viscosity [11] or an instability-driven viscosity [12], whichever is smaller at a given time. Disk material spreading onto the planet is lost, while mass spreading beyond a_R is removed from the inner disk and added to the *N*-body code as new bodies. The Roche-interior disk and the orbiting bodies interact at the strongest Lindblad resonances, so that exterior moonlets gain angular momentum from the disk, and in turn cause the disk's outer edge to recoil inward. If a moonlet is scattered inward and passes within $2R_{\oplus}$, we assume it is tidally disrupted and add its mass and angular momentum to the disk. We neglect the orbital evolution of bodies due to tidal dissipation in the planet or the body itself as those processes affect the system on much longer timescales than considered here.

Accretion simulations: We have performed a suite of numerical simulations to study the accretion of a moonlet from disks similar to those produced by the impacts considered in [7]. The initial structure of the disk is adapted from that of the disk shown in Figure 6 of [7] (R. Rufu, personal communication). We consider disks with a total mass $0.1 - 1M_L$, with 30-50% inside the Roche limit, and a surface density profile for the outer disk $\sigma \propto r^{-\alpha}$ with $\alpha = 2 - 3$. The outer disk is composed of 600 bodies with a Size Frequency Distribution following a power-law with an exponent of -1.5 (a value typically used in previous works), and an outer edge from $5 - 9R_{\oplus}$. The produced disks have $0.99 \leq J_{spec} \leq 1.2$, while [7] finds disks with $0.7 \leq J_{spec} \leq 1.14$. Disks with lower J_{spec} will be considered in follow-up work.

Figure 1 shows snapshots from a simulation of a disk with $0.5M_L$ and 50% of the mass in the inner disk, and an outer edge at $7R_{\oplus}$. The material initially in the outer disk rapidly accumulates into a single large object (Figure 1b). The inner disk has been confined well inside a_R due to resonant interaction with outer bodies. The disk viscously spreads out and new bodies are produced once its outer edge reaches a_R (Figure 1c). These objects recoil due to interactions with the inner disk and can collide with the outer moonlet, or be scattered back into the disk. When the latter happens, the outer body gains angular momentum and its semi-major axis expands. The outer moonlet can also capture inner bodies in mean-motion resonances. As the latter get pushed by the inner disk, they transfer some angular momentum to the outer body, whose orbit expands.

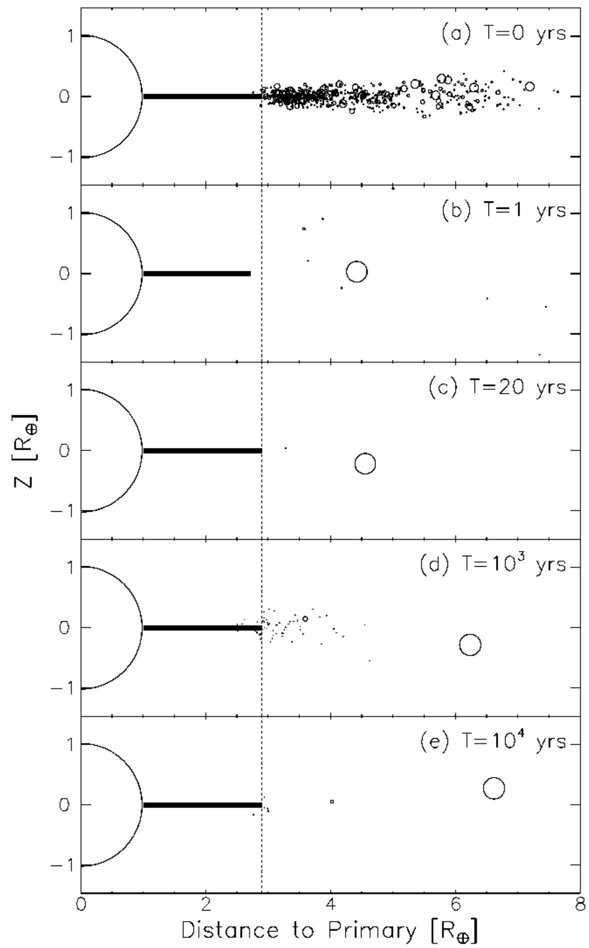

Figure 1: Snapshots of the protolunar disk, projected on the R−z plane, at t = 0, 1, 20, 10^3, and 10^4 years. The size of circles is proportional to the physical size of the corresponding particle. The horizontal thick line is the Roche-interior disk. The vertical dashed line is the Roche limit at $2.9R_{\oplus}$.

At 10^4 years of evolution, the Roche-interior disk mass has been decreased by a factor of 40 and the outer moonlet has a mass of $0.25M_L$ and a semi-major axis of $\sim 6.4R_{\oplus}$ (Figure 1e). Overall we find accretion dynamics similar to the canonical case, but the evolution timescale of the inner disk is longer because its mass, and thus its viscosity, is smaller than in the canonical case.

Figure 2 shows the mass of the largest object at 10^4 years as a function of the disk's initial specific angular momentum. The black triangles are results from a set of 60 simulations, while the red crosses are from the canonical case [5] and are shown for reference. The black lines are the analytical estimates from [8], considering either that 0 or 5% of the disk's mass escapes the system (continuous and dashed line, respectively). The blue lines are revised analytical estimates from [5].

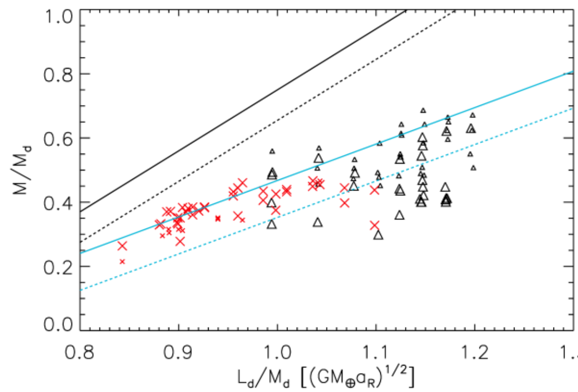

Figure 2: Ratio of the mass of the largest body at t = 10^4 years to the initial disk mass, as a function of the disk's initial specific angular momentum. Black triangles are results from the new set of simulations. Red crosses are from canonical disks [5] and are shown for reference. Small symbols are cases where the mass of the second largest body is at least 20% that of the largest one. In those cases we added the mass of the two bodies, since tidal evolution could cause them to merge later on [13]. The black solid and dashed lines are analytical estimates from [8] assuming 0 or 5% of the disk's mass escapes, respectively. Blue lines are our revised analytical estimates from [5].

We find good agreement between our numerical results and our revised analytical estimates (Figure 2, black triangles and blue lines). While our simulations do not cover the full range of possible disk J_{spec}, it appears that disks with $J_{spec} \geq 0.99$ would form a moonlet whose mass is about a factor of 2 smaller than predicted by [8]. If that trend continues at smaller J_{spec}, it is possible that twice as many impacts as estimated in [7] could be needed to form a lunar-mass object. This may affect the likelihood of a multiple-moon scenario, as a larger number of impacts would tend to decrease the probability of a final planet angular momentum comparable to that in the Earth-Moon system, due to the cancelation effects of retrograde vs. prograde impacts.

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