Three-stage lunar accretion: Slow growth of the Moon and implications for Earth-Moon isotopic similarities

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The Earth's Moon is believed to have accreted from a circumterrestrial disk generated by the impact of a Mars-size object into the proto-Earth [1]. N-body simulations of the disk's evolution generally produce a single massive moon in less than a year [2, 3]. However, the collisional energy dissipation rate implied by these models would substantially vaporize the inner disk, violating the model's assumption of a purely particulate disk. To accurately model the Moon's accretion and its formation timescale requires a model that accounts for the two-phase, fluid nature of the inner disk.

Disk material ejected by the impact is initially a mixture of melt and vapor [4]. Within the Roche limit, the disk evolves under two competitive processes [5, 6]: (1) gravitational instabilities in the melt, resulting in high collision rates, rapid viscous spreading, and vaporization due to energy released in collisions, and (2) radiative cooling of the gravitationally stable vapor phase, leading to its condensation. The balance of these processes regulates how rapidly the inner disk can spread and deliver material to the region exterior to the Roche limit where the Moon accretes.

Model

We have developed a new lunar accretion model (an improved version of [7]), in which Roche-interior material is represented by a fluid disk, while exterior moonlets are tracked with direct N-body simulation. We modified the symplectic integrator SyMBA [8] to include the tidal accretion criteria of [9] and a simple analytical model for the inner disk. We treat the inner disk as a uniform density slab of mass M_d, initially extending from the Earth's surface to the Roche limit at $a_R \approx 2.9R_\oplus$. The disk spreads viscously with either a radiation-limited viscosity [5] or an instability-driven viscosity [10], 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 moonlets.

The Roche-interior disk and the orbiting moonlets interact at 0-th order Lindblad resonances, so that exterior moonlets gain angular momentum from the disk, and in turn cause the disk's outer edge, r_d, to recoil inward. A scattered moonlet can be absorbed by the inner disk if it encounters a mass greater than its own during a single pass through the inner disk. We thus consider that any N-body particle with mass $< 0.1M_d$ and within an orbital radius $r < \gamma r_d$ is absorbed by the inner disk, where we let γ = 0 (no capture, bodies pass freely through the inner disk), 0.9 and 0.95. A captured particle is removed from the N-body simulation and its mass and angular momentum are added to that of the inner disk.

Results

We use initial configurations with a Roche-interior disk and an outer N-body disk, varying the total mass $M_T = M_d + M_{out}$, the masses in the inner (M_d) and outer (M_{out}) disks, the radial extent of the outer disk, and γ. We consider $2.0 \leqslant (M_T/M_☾) \leqslant 2.4$, motivated by results of [4, 11].

A typical simulation shows three accretion phases: (1) outer bodies collide and accrete in $\sim$ 1 yr and confine the inner disk within the Roche limit; (2) remaining moonlets recede due to disk torques, allowing the inner disk to viscously spread outward; and (3) the inner disk spreads back out to the Roche limit and spawns new moonlets that are accreted by the outer object(s) (Figures 1 and 2). The start of phase (3) is set by the slow, radiation-limited viscous spreading of the inner disk, and increases the final lunar accretion timescale to few $\times 10^2$ years, two orders-of-magnitude longer than that predicted by pure N-body simulations. An example simulation is shown in Figures 1 and 2.

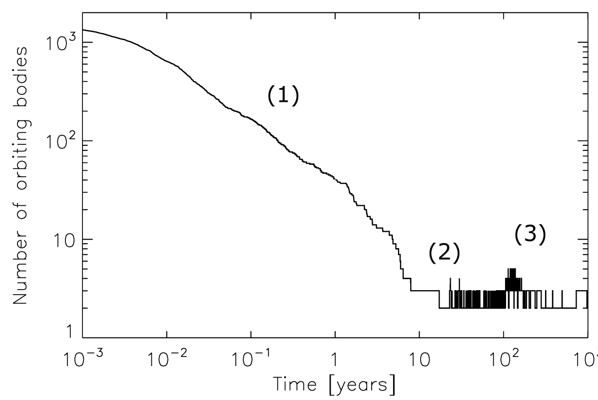

Figure 1: Number of N-body objects vs. time. Objects initially exterior to the Roche limit rapidly collide and accrete, and as they grow they increasingly confine the inner disk below a_R (1). Viscous spreading of the inner disk and outward migration of the moons allows the disk to re-expand to the Roche limit after $\approx$ 20 yr (2), and new moonlets spawned from the inner disk then accrete onto the moon over the next several hundred years (3). This simulation had γ = 0, with initial values $M_T = 2.4M_☾$, $M_d = 1.80M_☾$, and an outer disk with $M_{out} = 0.60M_☾$ and extending to $6R_\oplus$.

Figure 3 shows the fraction of the final Moon derived from the inner disk vs. the final Moon's mass at the end

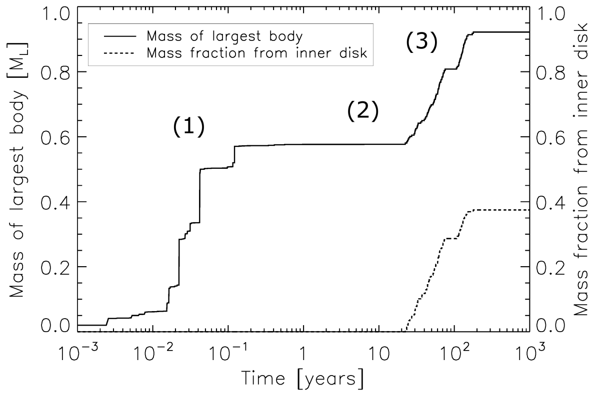

Figure 2: Mass of the largest moon (solid line), and the fraction of its mass composed of material derived from the Roche-interior disk (dashed line) for the simulation shown in Figure 1. It takes $\sim$ 200 years for the inner disk mass to be depleted and for the moon to reach its final mass of $0.92 M_{☾}$, 37% of which originated in the inner disk.

of our simulations. Colors correspond to $\gamma = 0$ (black), 0.90 (green), and 0.95 (red). Allowing bodies to be absorbed by the disk if they pass within it increases the predicted fraction of inner disk material that ends up in the Moon. However, bodies with a mass $> 0.8\ M_{☾}$ have $< 60\%$ of their mass derived from the inner disk.

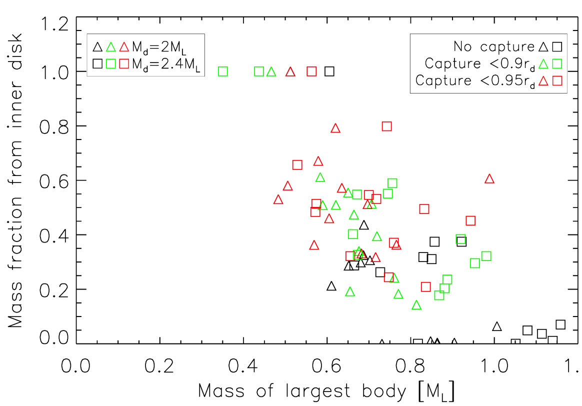

Figure 3: Fraction of the largest body derived from material in the Roche-interior disk vs. the mass of the largest body, for different capture criteria. For cases where the 2nd largest body has a mass $> 30\%$ that of the largest, we plot the summed mass and mass fraction for the pair. Black points are simulations where N-body objects pass freely through the inner disk, while green and red points correspond to cases where bodies are assumed to be absorbed by the inner disk if they pass within $0.9 r_d$ or $0.95 r_d$, respectively, and have masses $< 0.1 M_d(t)$.

Discussion

Consideration of a radiation-limited inner disk alters the nature of lunar accretion relative to that seen in prior pure N-body models. Material initially orbiting outside the Roche limit still accretes very rapidly (in months), but delivery of material from the Roche-interior disk proceeds slowly, resulting in a total lunar accretion timescale of $\sim 10^2$ years.

Moon-disk resonant interactions limit the fraction of the inner disk that is ultimately incorporated into the final Moon. The 3-phase accretion process found in our simulations implies that only material accreted during the final stage is derived from the inner disk, for an initial outer disk mass $M_{out} \geqslant few \times 10^{-1} M_{☾}$.

If isotopic equilibration occurs between Earth's atmosphere and the inner vapor disk [12], Earth-like material could then be concentrated in the outer portions of the Moon, depending on the degree of mixing during phase (3). However for appropriately large moons, the fraction of the final moon comprised of material processed through the inner disk remains fairly small, typically less than 0.5. For a $1 M_{☾}$ moon, such a fraction would represent a $\leqslant$ 350 km-deep outer layer. Further improvements, in particular a full numerical simulation of the Roche-interior disk [13, 14] that accounts for the radial dependence of the disk viscosity, may result in an increased fraction of inner disk material in the final Moon. A compact, $M_T > 3 M_{☾}$ initial disk would also increase this fraction, although such protolunar disks have not been produced by impact simulations to date.

Acknowledgements

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