How much Earth-like material could the Moon accrete?

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Introduction

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]. A key constraint is explaining the similar compositions of the Earth and the Moon (O-isotopes in particular [2]). Most impact simulations find that the majority of the disk material comes from the impactor [3, 4], which is thought to have had a composition significantly different from that of the Earth, given the observed compositional variations between the Earth and other inner Solar System objects [5].

Disk material within the Roche limit can be described as a two-phase, melt-vapor fluid that evolves under two competitive processes [6, 7]: (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.

It has been proposed that diffusive mixing between the Earth's and the disk's atmospheres could chemically equilibrate the disk with the Earth in $\sim 10^2$ to 10^3 years [5]. Prior N-body simulations of Moon formation from a circumterrestrial disk found rapid accretion in less than a year [8, 9], although these were purely particulate models that did not account for a two phase, Roche-interior disk.

Model

In our model (an improved version of [10]), material within the Roche limit is represented by a fluid disk, while exterior moonlets are tracked with direct N-body simulation. We have modified SyMBA [11] to include the accretion criterion of [12] 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 $a_R \approx 2.9 R_\oplus$. The disk spreads viscously with either a radiation-limited viscosity [6] or an instability-driven viscosity [13], 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 disk and added to the N-body code as new moonlets.

Interactions between the disk and the orbiting bodies at 0-th order Lindblad resonances result in an additional "kick" to the orbiting bodies, which gain angular momentum from the disk and cause the disk's outer edge, r_d, to recoil inward. The disk would efficiently absorb scattered objects small enough to encounter a disk mass greater than their own during a single pass through the inner disk. We thus consider that any N-body particle with mass $< 0.1 M_d$ and within an orbital radius $r < \gamma r_d$ is absorbed by the inner disk, where we let $\gamma = 0$ (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 added to that of the disk.

Results

We use initial configurations with a Roche-interior disk and an outer N-body disk, varying the total mass in the inner and outer disks (M_T) and the radial extent of the outer disk.

A typical simulation shows three accretion phases: (1) outer bodies rapidly accrete and confine the inner disk within the Roche limit; (2) remaining orbiting objects recede due to torques from the disk, 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) (Figure 1). The start of phase (3) is regulated by the slow, radiation-limited viscous spreading of the disk, and increases the final accretion timescale to several hundreds of years, which could be compatible with required timescales for equilibration. An example evolution of the mass of the largest body and the fraction of its mass derived from the inner disk is plotted in Figure 2.

Figure 3 shows the fraction of the final Moon derived from the inner disk vs. the final Moon's mass at the end of simulations that considered M_T = 2 to $2.4 M_☾$. Colors correspond to different values of γ: 0 (black), 0.90 (green), and 0.95 (red). Allowing bodies that pass within the disk to be absorbed by the disk significantly increases the predicted fraction of inner disk material that ends up on the Moon. However, bodies with a mass $> 0.8\ M_☾$ have $< 55\%$ of their mass derived from the inner disk.

Discussion

Material initially orbiting exterior to the Roche limit 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

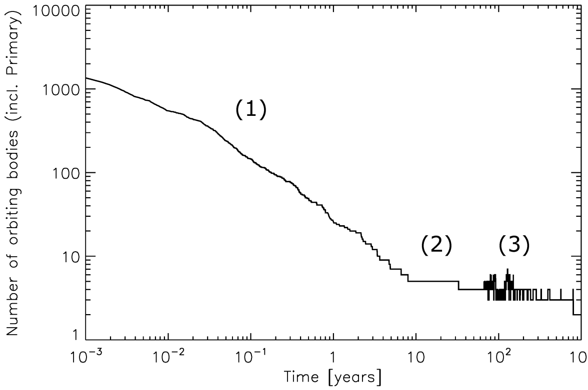

Figure 1: Evolution of the number of orbiting bodies. First orbiting objects collide and accrete, and they confine the inner disk below the Roche limit (1). Viscous spreading and outward migration of the moons allow the disk to reach the Roche limit (2), and new moonlets are produced and finally accrete on the moon (3). This simulation had $M_d = 1.50 M_{\leftmoon}$, and an initial outer disk with $0.50 M_{\leftmoon}$ and extending to $4R_\oplus$.

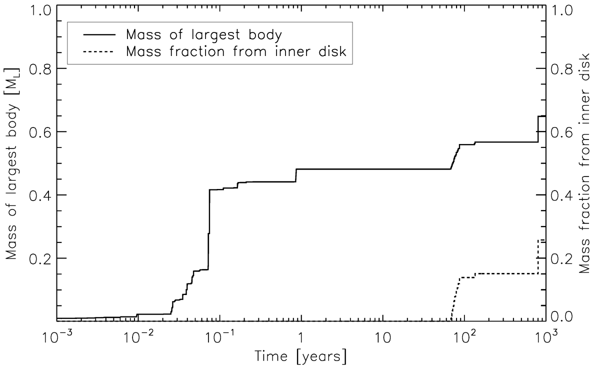

Figure 2: Mass of the largest body (solid line), and the fraction of its mass composed of material derived from the Roche-interior disk (dashed line) for the simulation shown in Figure 1. First the largest body grows through collisions and confines the ring below the Roche limit. As the body recedes away through resonant interactions, the inner disk can spread back out to the Roche limit. Then new moonlets are spawned, and growth of the Moon continues. After $\sim$ 200 years, the inner disk is depleted and the moon reaches its final mass of $0.65 M_{\leftmoon}$, 25% of which originated in the inner disk.

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. Provided equilibration can occur, Earth-like material might then be concentrated in the outer portions of the Moon, depending on whether there is substantial cooling of the Moon between phases (1) and (3). For appropriately large moons, the fraction of the Moon comprised of equilibrated material remains fairly small, typically less than 0.5. Further improvements, in particular a full numerical simulation of the Roche-interior disk [14, 15] 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, $M_T > 3M_{\leftmoon}$ initial disk would also increase this fraction, although such disks have not been produced by impact simulations.

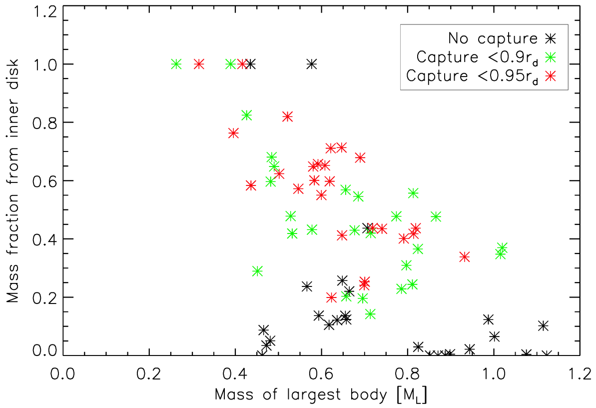

Figure 3: Mass fraction of the Moon composed of material accreted from the Roche-interior disk vs. the mass of the largest body, for different capture criteria. For cases where the 2nd largest body has a mass $> 30\%$ that of the largest, we plot the mass and mass fraction of the combined body. Black 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 $0.9r_d$ or $0.95r_d$, respectively. Allowing capture of bodies in the inner disk significantly increases the mass fraction of inner disk material that ends up on the Moon.

Acknowledgements

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