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Lunar accretion from a Roche-interior fluid disk

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Abstract

We use a hybrid numerical approach to simulate the formation of the Moon from a circumterrestrial disk: a fluid disk to model the disk inside the Roche limit, and an N-body code for the outer particles. As the fluid disk spreads due to its viscosity, new material is delivered across the Roche limit and accreetes in moonlets that can then collide to form the Moon. Contrary to an accretion timescale of a few months obtained with pure N-body codes, the growth of the moon is here limited by the slow spreading of the inner disk, resulting in accretion timescales up to hundreds of years.

1. Introduction

The generally accepted scenario for the formation of the Earth's Moon involves the impact of a Mars-size object onto the proto-Earth, resulting in the formation of a disk around the Earth, from which the Moon accreted [1]. Simulations of the impact show that most of the material composing the disk comes from the impactor [2, 3]. However, this object would likely have a composition much different from that of the Earth, which fails to explain the almost identical compositions of the Earth and the Moon (O-isotopes in particular [4]).

The Roche-interior disk can be modeled as a two-phase melt-vapor fluid. Its evolution is regulated by 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.

It has been proposed that mixing could occur between the Earth's and disk's atmospheres, leading to an equilibration of the disk's composition with that of the Earth. The timescale for equilibration to occur has been estimated at 100-1000 years [7]. However, prior numerical simulations of Moon formation from a circumterrestrial disk have given accretion timescales of less than a year [8, 9]. More accurate modeling of the fluid inner disk is needed.

2. The Model

In this work we model material within the Roche limit by a fluid disk, while exterior material is tracked with direct N-body simulation. Our model is an improved version of [10]. We use the symplectic integrator SyMBA [11], in which we have included a simple model for an inner fluid disk, and a more accurate treatment of collisions using the tidal accretion criterion of [12]. Interactions between the disk and the orbiting bodies at 0-th order Lindblad resonances result in an additional "kick" in the computation of the orbital evolution of the bodies.

The inner disk is 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 following effects are taken into account:

- **Viscous torque** We consider a radiation-limited viscosity [5] or an instability-driven viscosity [13, 14] for the inner disk, whichever is smaller at a given time.
- **Resonant torque** At each "kick" we compute the total torque exerted by the moonlets on the disk, and as a first approximation we apply that torque by shifting the disk's outer edge.
- **Moonlets spawning** If the viscous torque is smaller than the resonant torque, then the disk is repelled inward. If not, it spreads outward, and when it reaches the Roche limit, the mass flowing outward is removed from the disk and we add a new moonlet of the corresponding mass to the N-body code. Mass loss also occurs through the disk's inner edge by infall onto the planet.

3. Results

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

A typical simulation shows a three-steps accretion of the Moon: (1) the outer bodies collide and accreete, and confine the inner disk within the Roche limit, and the disk begins losing mass to the planet, (2) the remaining orbiting object(s) recede due to torques from the disk, allowing the disk to spread outward, and (3) the inner disk reaches the Roche limit, new moonlets are spawned and collide with the outer object (Figure 1). The accretion is then regulated by the slow radiation-limited viscous spreading of the disk, increasing the final accretion timescale to several hundreds of years. An example of the evolution of the masses of the inner disk, of the most massive moon, and of the mass lost on the planet, are plotted in Figure 2.

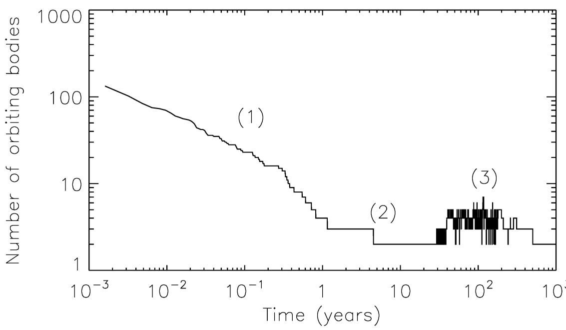

Figure 1: Evolution of the number of orbiting bodies. First orbiting objects collide and accreete, and they confine the inner disk below the Roche limit (1). Viscous spreading and outward migration of the moons allow the disk to reach the Roche limit (2), and new moonlets are produced and finally accrete on the moon (3).

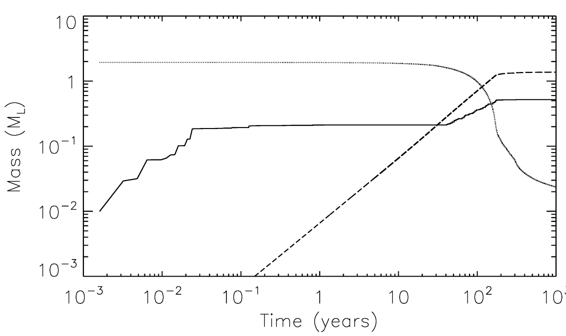

Figure 2: Mass of the largest orbiting body (solid line), of the inner disk (dotted line), and total mass fallen on the planet (dashed line), for an initial spreading timescale of 100 years. First the largest body grows through collisions and confines the ring below the Roche limit. Then the inner disk reaches the Roche limit, new moonlets are spawned allowing the largest body to grow again. After $\sim$ 200 years, the inner disk is depleted and the moon reaches its final mass. This simulation had $M_d = 1.94 M_☾$, and an initial outer disk with $0.22 M_☾$ and extending to $1.25 a_R$.

The moon accretion timescale depends directly on the spreading timescale of the inner disk, for which we use [5]:

$$\tau = 100 \left(\frac{r_d}{a_R}\right)^{-3} \left(\frac{T_p}{2000K}\right)^{-4} \left(\frac{M_d}{2M_☾}\right) yr \quad (1)$$

where r_d is the inner disk's outer edge, and T_p is the disk's photospheric temperature. For standard values ($r_d = a_R$, $T_p = 2000K$ and $M_d = 2M_☾$), $\tau = 100$ years. This is the value used in Figure 2, for which the final mass of the Moon is obtained in ~ 200 years.

Future improvements to the code will include numerical simulation of the inner disk evolution [14, 15], and consideration of recent alternate models for the inner disk [6].

Acknowledgements

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