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# N-body Simulation of the Evolution of a Protolunar Disk

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**Abstract.** We performed $N$-body simulations of dense particulate disks and quantitatively analyzed angular momentum transfer processes therein. Angular momentum transfer is dominated by both gravitational torque and particles' collective motion associated with the structure. These processes depend on surface density, and do not depend on particle size or number if the structure is resolved enough.

## 1. Introduction

The most favored scenario of the origin of the Moon is Giant Impact Hypothesis (Hartmann & Davis 1975, Cameron and Ward 1976). In this scenario, Mars-sized protoplanet collided to the proto Earth. It is considered that the Moon was formed from the circumterrestrial debris disk, which is splashed by the impact. Ida et al. (1997) and Kokubo et al. (2000) performed $N$-body simulations of the lunar accretional process, and showed that a single Moon is formed from the debris disk just beyond the Roche limit within a month to a year. They suggested that the development of spiral structure due to self gravitational instability is essential to the evolution of the disk. To clarify the evolution of the protolunar disk, we performed $N$-body simulation using up to 100,000 particles and analyzed the details of angular momentum transfer processes.

## 2. Angular Momentum Transfer

The protolunar disk transfers angular momentum outward. Thus, inner materials of the disk lose angular momentum and fall inward and outer materials migrate outward in compensation. Materials which migrate beyond Roche limit form the Moon (Ida et al. 1997). The angular momentum transfer in particulate disk is classified to three processes (Takeda and Ida 2001). 1. Due to epicyclic excursion, particles can deposit the angular momentum to nearby regions by the collision. This transfer is analogous to the transfer by molecular viscosity. 2. Angular momentum is transfered from particle to particle by collision itself. 3. Trailing spiral structure transfer angular momentum outward by gravitational



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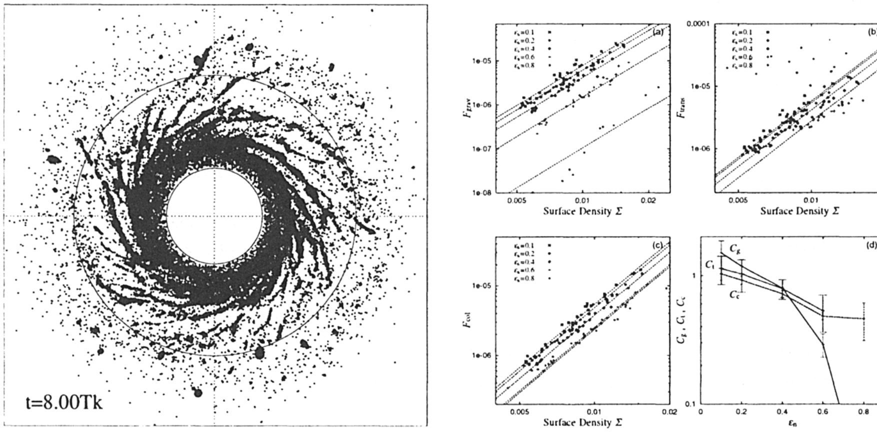


Figure 1. Snapshot (left), and angular momentum transfer as function of surface density (a,b and c), and of restitution coefficient (d).

torque. We analyzed above processes in $N$-body simulation, including both self-gravity and mutual collisions.

## 3. Result

Left panel of Figure 1 shows the snapshot. As the random velocity is damped by inelastic collisions, spiral structure develops. Spiral arms are successively sheared apart by tidal effect and reformed by self gravitational instability. Since self-gravitational instability is regulated by surface density, angular momentum transfer rate is regulated by surface density. Panel (a), (b), and (c) show the angular momentum transfer rate as a function of surface density. The transfer rates are proportional to $\Sigma^3$. They does not depend on the particle size or number as long as spiral structure is well resolved. Angular momentum transfer rate slightly decreases as restitution coefficient increases (panel (d)), since damping of random velocity is essential in the development of spiral structure. With restitution coefficient greater than 0.8, no spiral structure appears. With these result, we conclude that the time scale of the disk evolution and lunar accretion are determined by surface density only, and the validity of previous simulations are confirmed. As for the details of the results, see Takeda and Ida 2001.

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