N-body Simulation of Planetesimal Formation Through Gravitational Instability of a Dust Layer in Laminar Gas Disk

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In the standard scenario of planet formation, planetesimals are the precursors of planets. Their formation process is one of the unsolved problems of the planet formation theory. Beginning with micron-sized dust grains, they grow to centimeter size in a protoplanetary disk via collisional agglomeration. The least understood growth phase is growth from centimeter size to kilometer size.

One of the possible models for planetesimal formation is the gravitational instability model. A very thin and dense layer of settled dust aggregates in the mid-plane of the protoplanetary disk may be gravitationally unstable. Then the gravitational collapse of the dust layer occurs, and kilometer-sized planetesimals are formed directly. This scenario has the advantage of a very rapid formation timescale, which is on the order of the Keplerian time.

The linear analyses of the gravitational instability of dust layers have been performed extensively[1]. However, the nonlinear stage of the gravitational instability has not been studied well. We have investigated the planetesimal formation by gravitational instability by local N-body simulations[2,3]. In this study, we have considered the effect of gas drag force[4].

According to the linear analysis of gravitational instability without gas drag force, the stability of the disk is characterized by Toomre's Q value. When $Q < 1$, the disk is unstable. On the other hand, the linear analysis with gas drag force shows that the dust layer is always secularly unstable although Toomre's Q value is larger than unity.

In the initial stage, the growth time of the gravitational instability is longer than the timescales of the dust sedimentation and the decrease of the velocity dispersion. Thus, the velocity dispersion decreases and the disk shrinks vertically. As the velocity dispersion becomes sufficiently small, the gravitational instability finally becomes dominant.

We found that the the formation process is divided into three stages qualitatively: the formation of wakelike density structures, the creation of planetesimal seeds, and their collisional growth.

The top-right panel of Figure 1 shows the first stage of the planetesimal formation. The non-axisymmetric density structures appear. These structures are well-known in the dense planetary rings, which are caused by the gravitational instability.

As shown in the left-bottom panel of Figure 1, in the dense part of wakes, the wakes break into many fragment due to self-gravity. These are the planetesimal seeds. After the formation of planetesimal seeds, the rapid collisional growth begins. Several large planetesimals are formed and absorb almost all small particles.

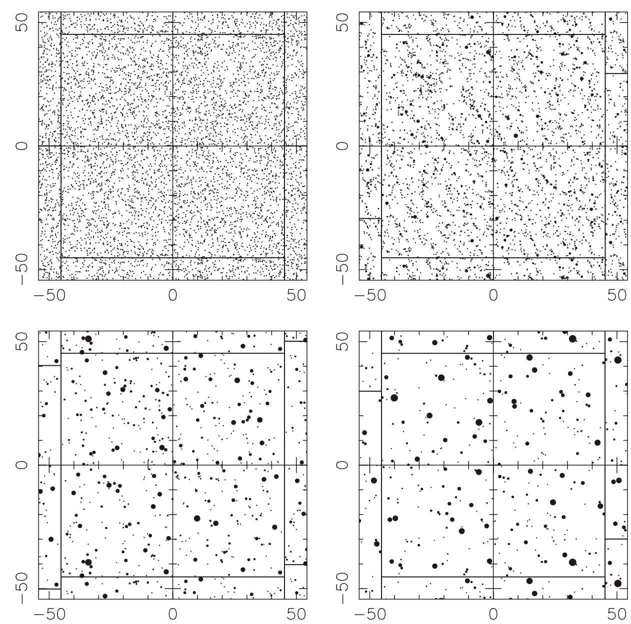

Figure 1: The snapshots of the N-body simulation of the planetesimal formation at $t = 0.0\ T_K$ (top-left), $t = 0.4\ T_K$ (top-right), $t = 0.8\ T_K$ (bottom-left), $t = 1.2\ T_K$ (bottom-right), where T_K is Keplerian period.

References

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[3] Michikoshi, S., Kokubo, E., Inutsuka, S.-i.: 2009, *ApJ*, **703**, 1363.
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